

Heavy quarkonia and cold nuclear matter

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New results from LHC and RHIC

Introduction

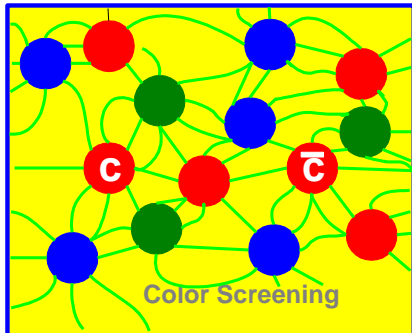
Heavy quarkonia in HI collisions (1)

Heavy quarkonia are good candidates to probe the QGP in heavy ion collisions because:

- they have large masses and are (dominantly) produced at the early stage of the collision, via hard-scattering of gluons.
- they are strongly bound (small radius) and weakly coupled to light mesons.

	mass	radius
J/ψ	3.1 GeV	0.50 fm
Υ	9.5 GeV	0.28 fm

Sensitive to the formation of a quark gluon plasma via color screening:



State	J/ψ	Υ
T_{dis}	$1.2 T_c$	$2 T_c$

T_c : QGP formation temperature

T_{dis} : quarkonia dissociation temperature

Heavy quarkonia in HI collisions (2)

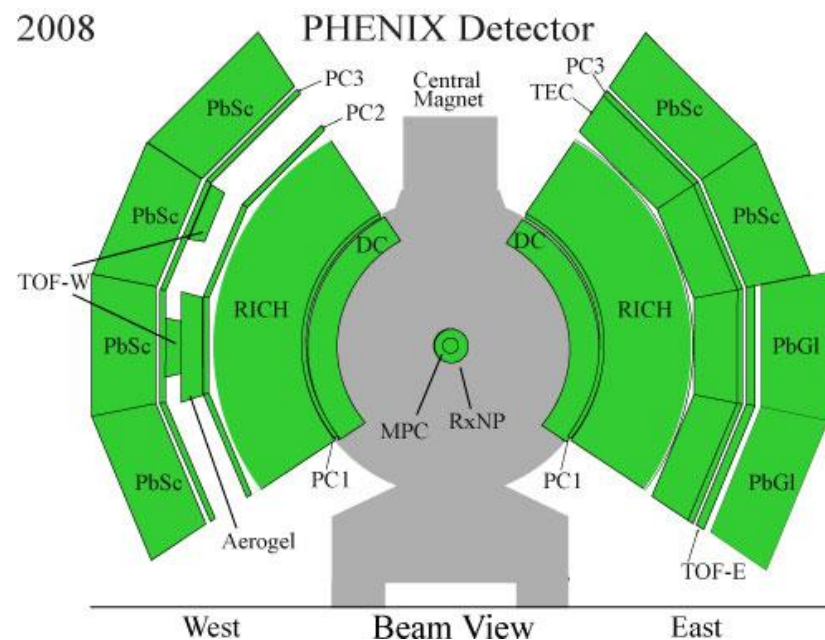
However:

1. Although heavy quarkonia are hard probes, the production mechanism (in $p+p$) is not well understood;
2. There are many effects that can alter this production in presence of normal nuclear matter (in e.g. $p(d)+A$);
3. It is unclear how to extrapolate, and subtract these effects from what is measured in $A+A$, to single-out QGP effects.

Still:

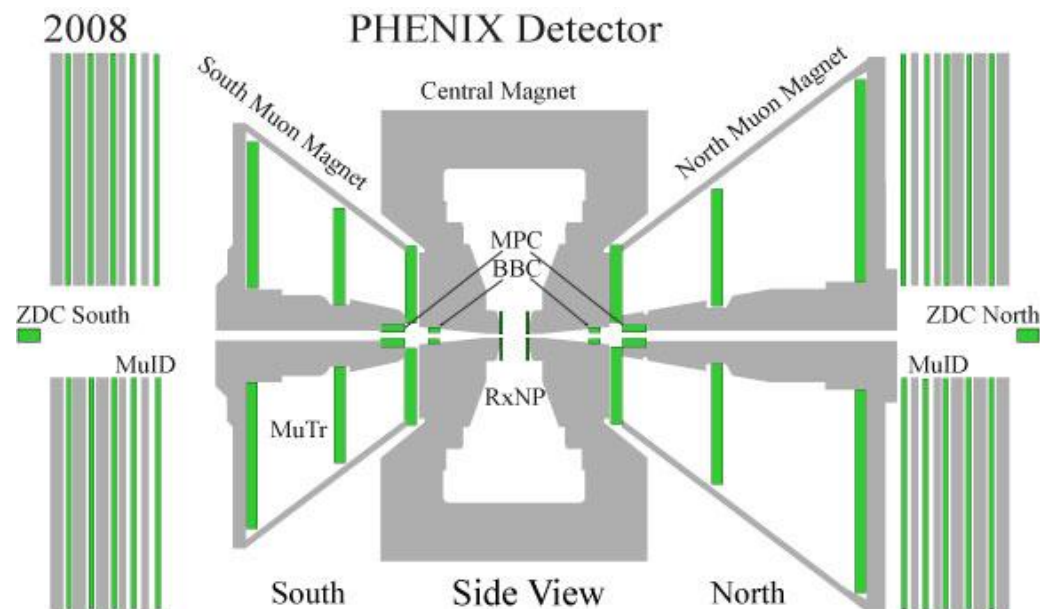
As a resonance, heavy quarkonia are *easy* to measure (and separate from background) as opposed to most other hard probes (photons, open heavy flavors, jets)

Heavy quarkonia measurements in PHENIX



Mid rapidity: $J/\psi, Y \rightarrow e^+e^-$
 $|\eta| < 0.35$, $\Delta\Phi = 2 \times \pi/2$, $p > 0.2$ GeV/c

Electrons identified using RICH and EMCAL; tracked using pad and drift chambers



Forward rapidity: $J/\psi, Y \rightarrow \mu^+\mu^-$
 $1.2 < |\eta| < 2.2$, $\Delta\Phi = 2\pi$, $p > 2$ GeV/c

Muons identified using layered absorber + Iarocci tubes; tracked using 3 stations of cathode strip chambers, in radial magnetic field

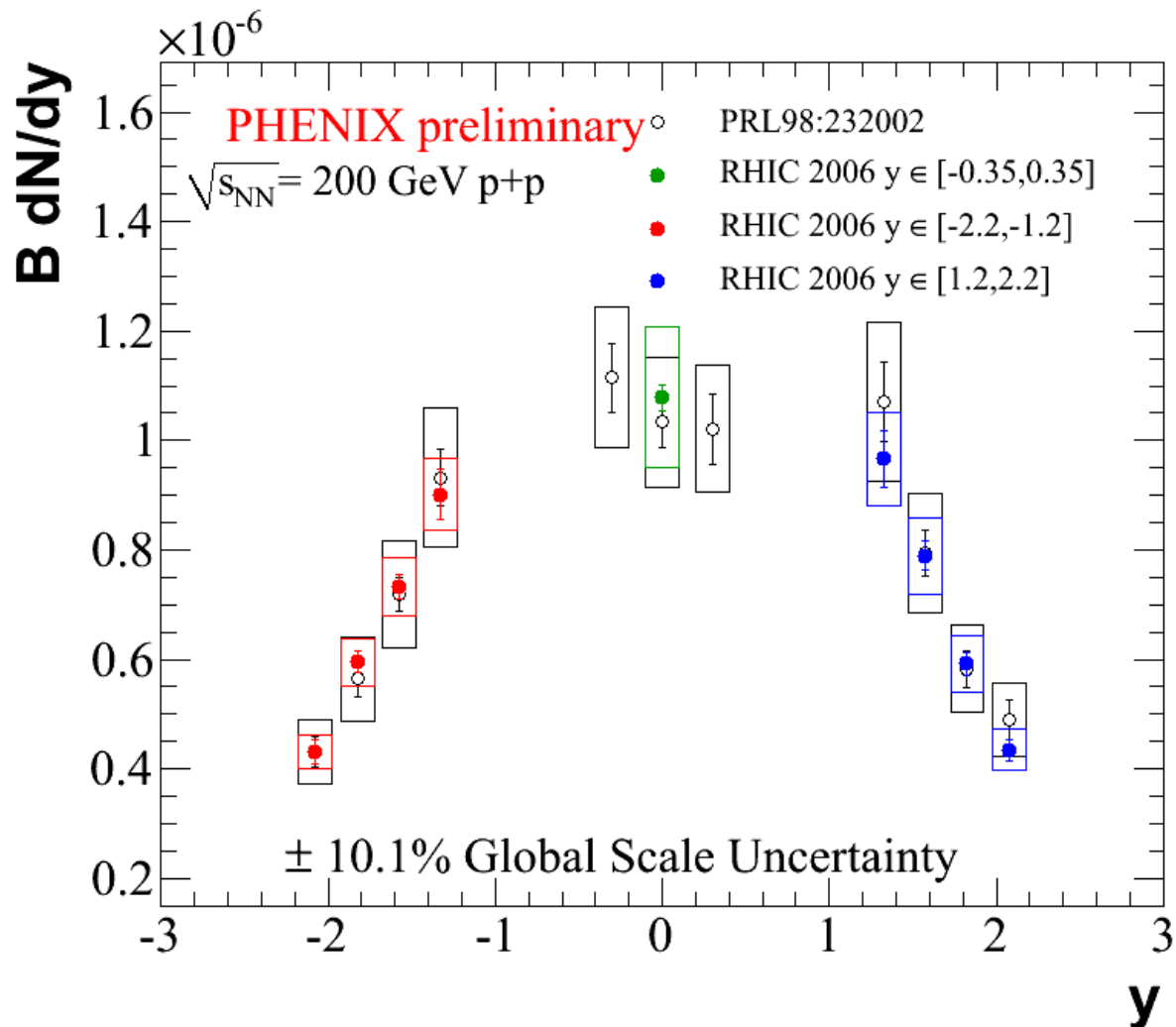
Outline

- p+p collisions:
production mechanism
baseline for heavy ions
- d+Au collisions:
cold nuclear matter effects
- Cu+Cu and Au+Au:
hot nuclear matter effects

I. p+p collisions:

- production mechanism**
- baseline for d+A and A+A collisions**

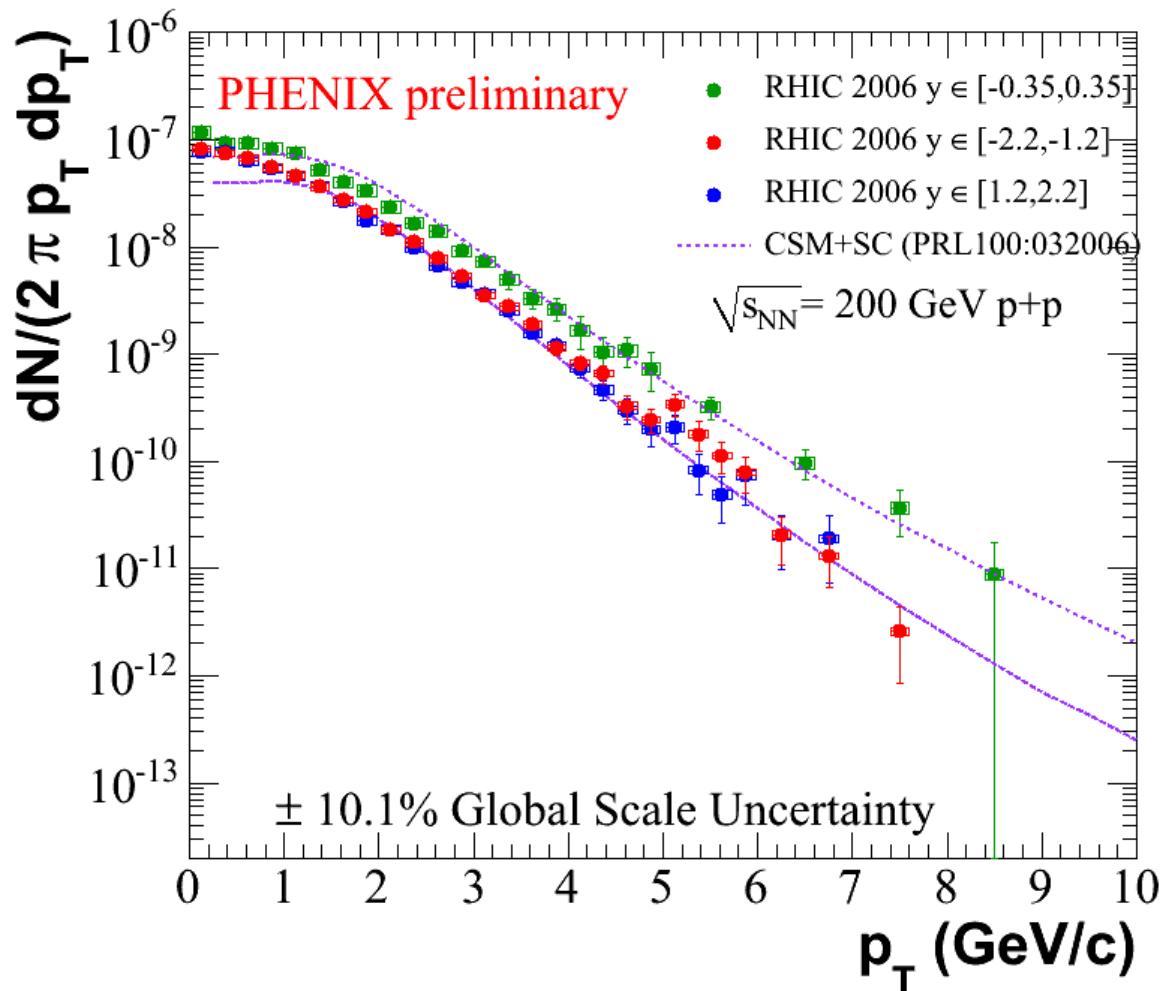
J/ψ measurements (1)



Higher statistics and better control over systematics
Excellent agreement with published results

\Rightarrow Better constraints on models

J/ψ measurements (2)



Excellent agreement between data at positive and negative rapidity

Harder spectra observed at mid-rapidity.

Production mechanism

Several models available, that differ mainly on how the $c\bar{c}$ pair formed during the initial parton scattering (gg at RHIC) is neutralized prior to forming the J/ψ

- **Color Evaporation Model (CEM)**

Heavy quarkonia production is considered proportional to the $c\bar{c}$ cross-section. The proportionality factor is fitted to data. It is independent from p_T and rapidity.

- **NRQCD, or Color Octet Model (COM) NLO, NNLO***

the $c\bar{c}$ pair can be produced in an octet state. The neutralization is realized non-perturbatively via exchange of multiple soft gluons, that do not affect the initial $c\bar{c}$ kinematics.

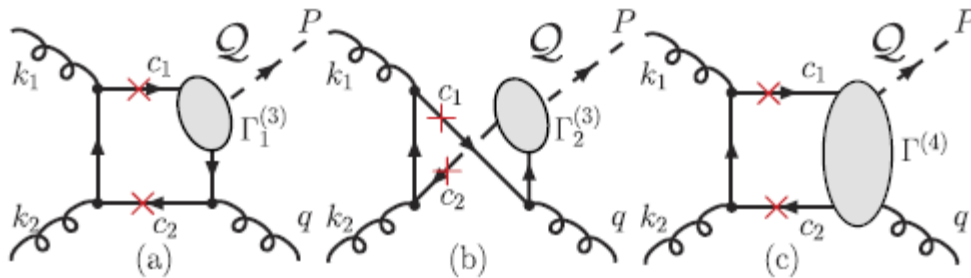
- **Color Singlet Model (CSM) NLO, NNLO***

at LO, a third hard gluons is use to neutralized the $c\bar{c}$ pair.

Production mechanism (2)

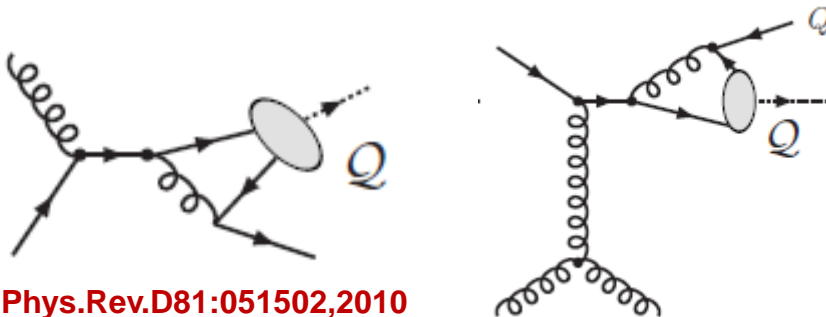
Recent developments on CSM

- **s-channel cut:** allow the $c\bar{c}$ pair to be off-shell, prior to interaction with the 3rd hard gluon



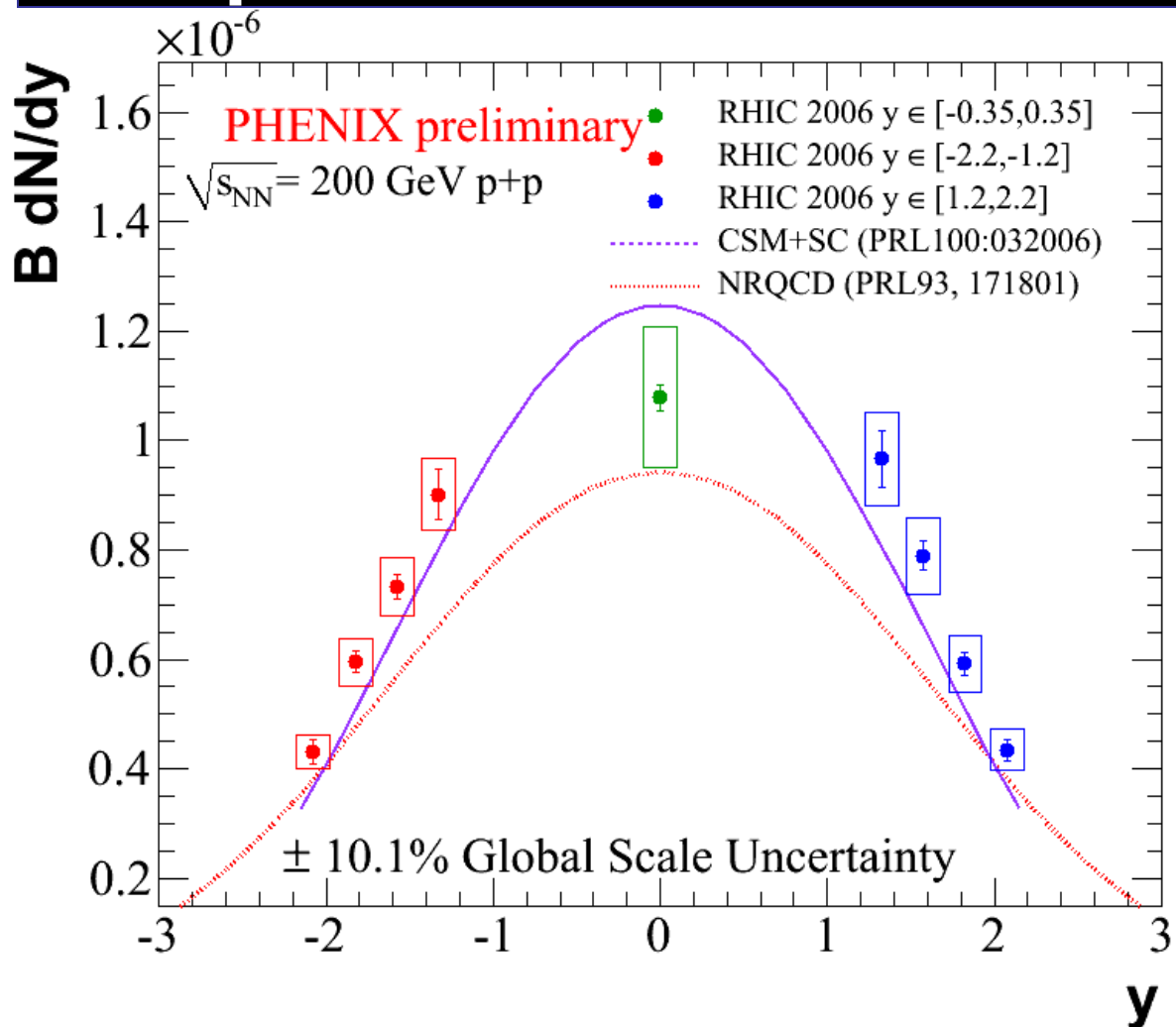
PRL 100, 032006 (2008)

- CSM at LO, NLO (@RHIC), NNLO* (@Fermilab)
- Accounting for J/ψ production from “intrinsic” charm (taken from one of the incoming protons)



Phys.Rev.D81:051502,2010

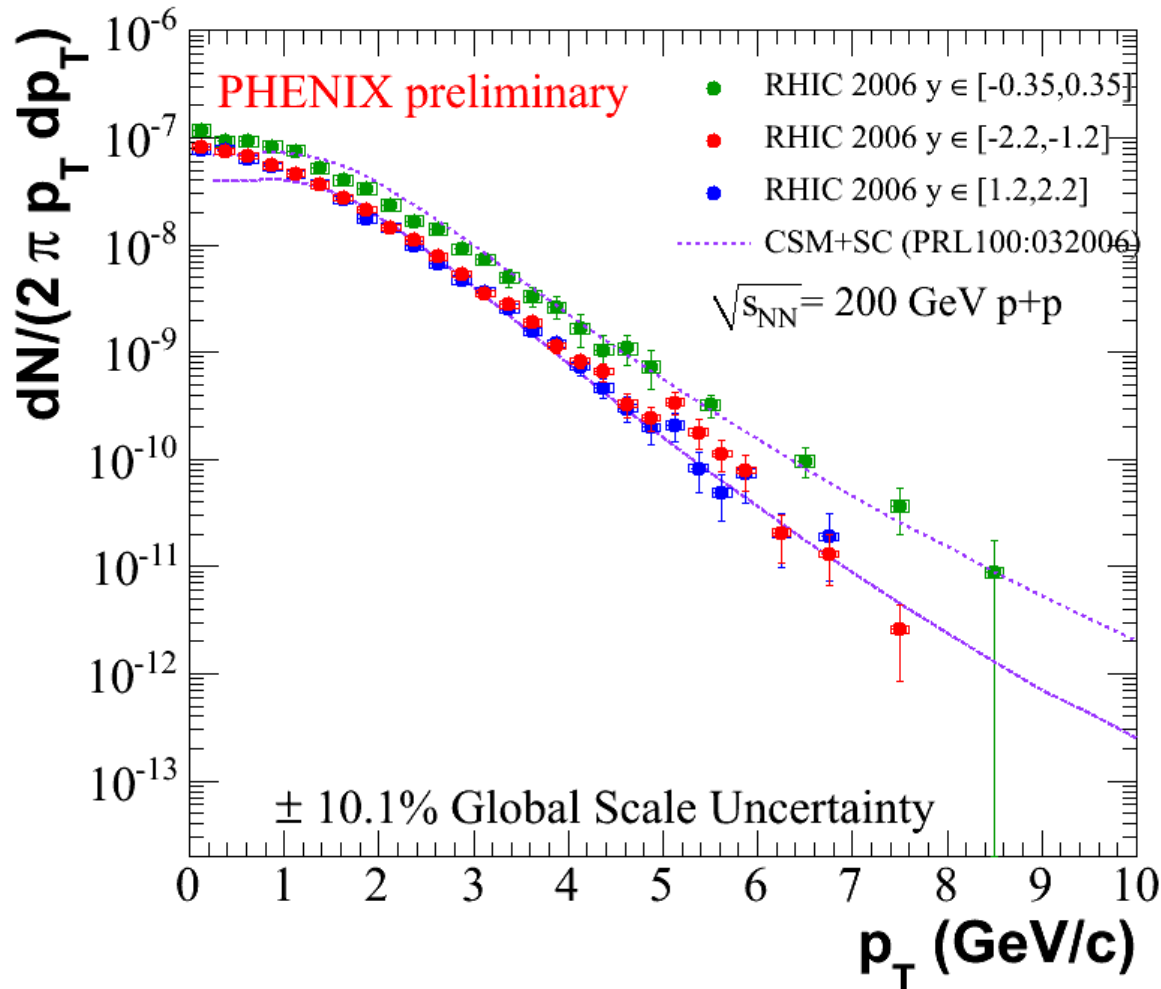
Comparison to models



Models have absolute normalization; they are not scaled to the data.

CSM (LO)+S channel cut, tuned (parametrized) to CDF, does a fairly good job at reproducing PHENIX data.

Comparison to models

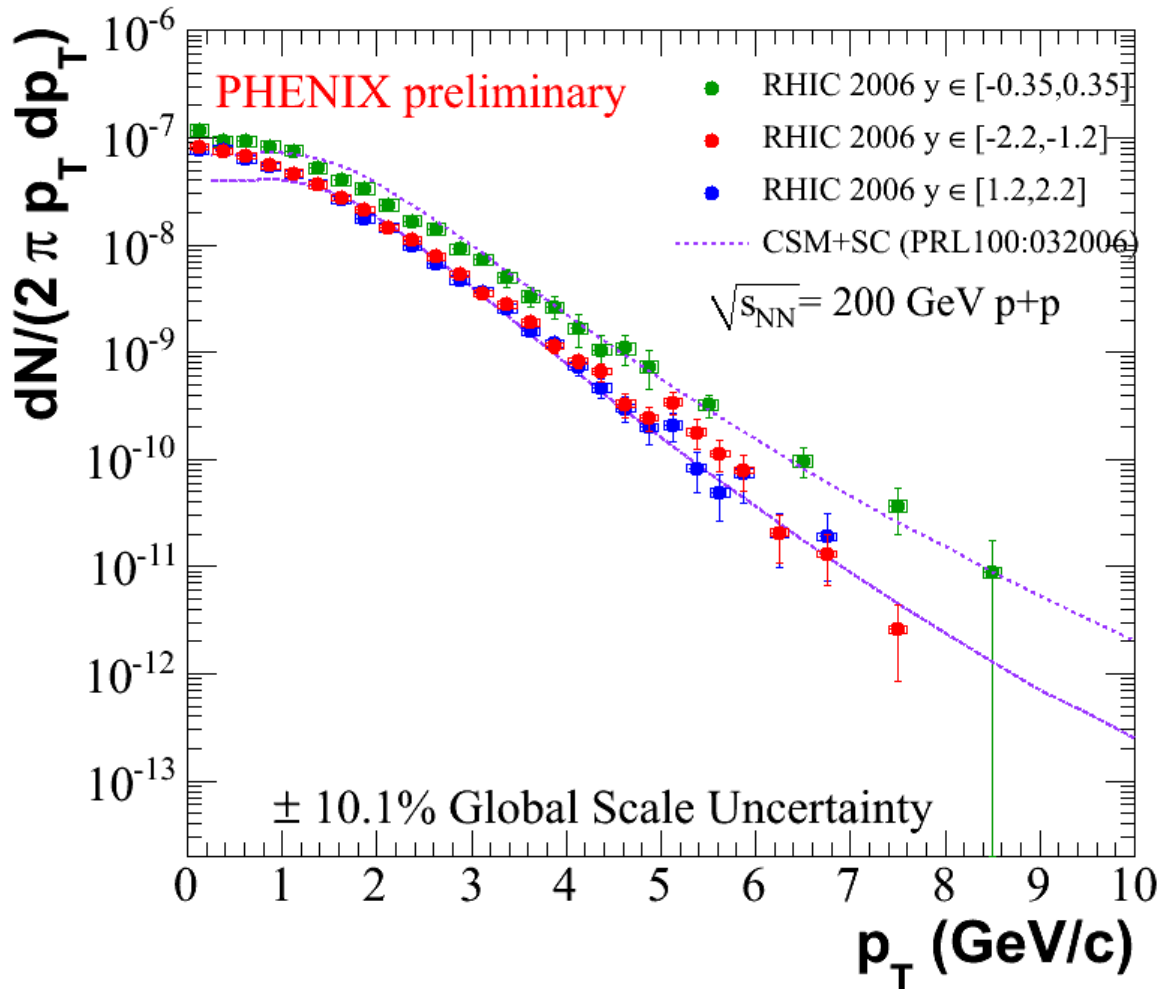


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Very good agreement also achieved vs p_T .

Comparison to models



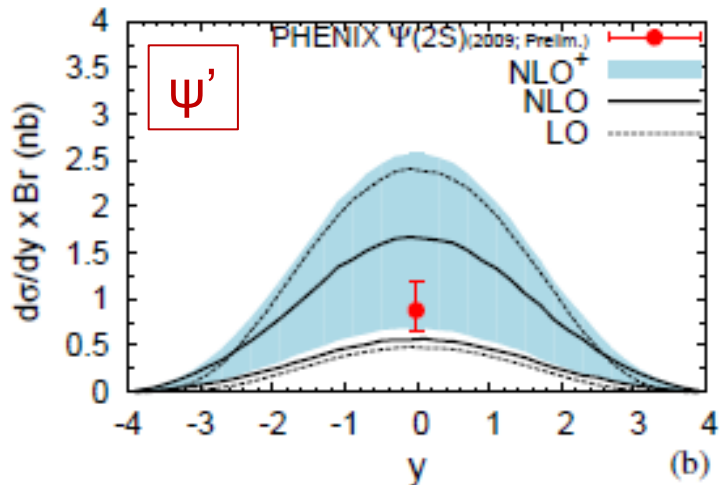
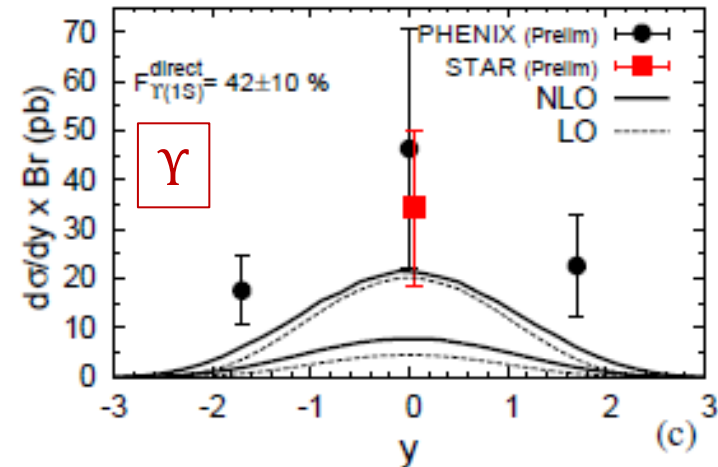
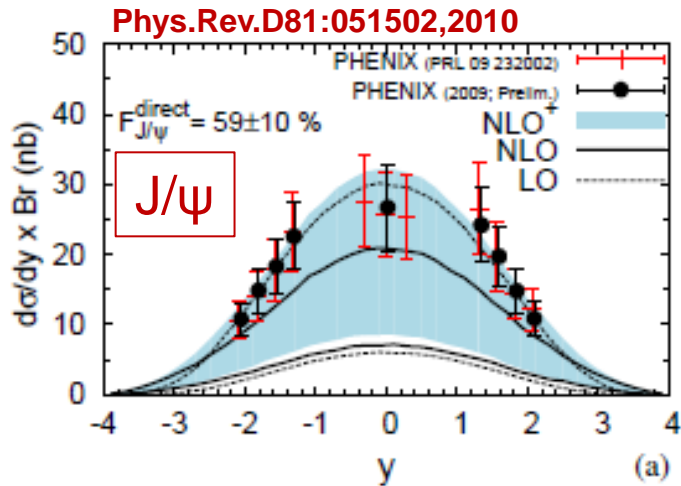
Models have absolute normalization; they are not scaled to the data.

CSM (LO)+S channel cut, tuned (parametrized) to CDF, does a fairly good job at reproducing PHENIX data.

Very good agreement also achieved vs p_T .

However there are concerns about the validity of s-channel cut approach and the magnitude of the obtained contribution
[PRD 80, 034018 (2009)]

CSM at NLO + Intrinsic Charm



PHENIX J/ψ data are scaled down by $\sim 60\%$ to remove decay contributions.

Only p_T integrated calculations are available.

NLO contribution is negative and smaller than LO. Allows reduction of the theoretical uncertainty.

IC contribution is of the same order as NLO gluon fusion, with opposite sign.

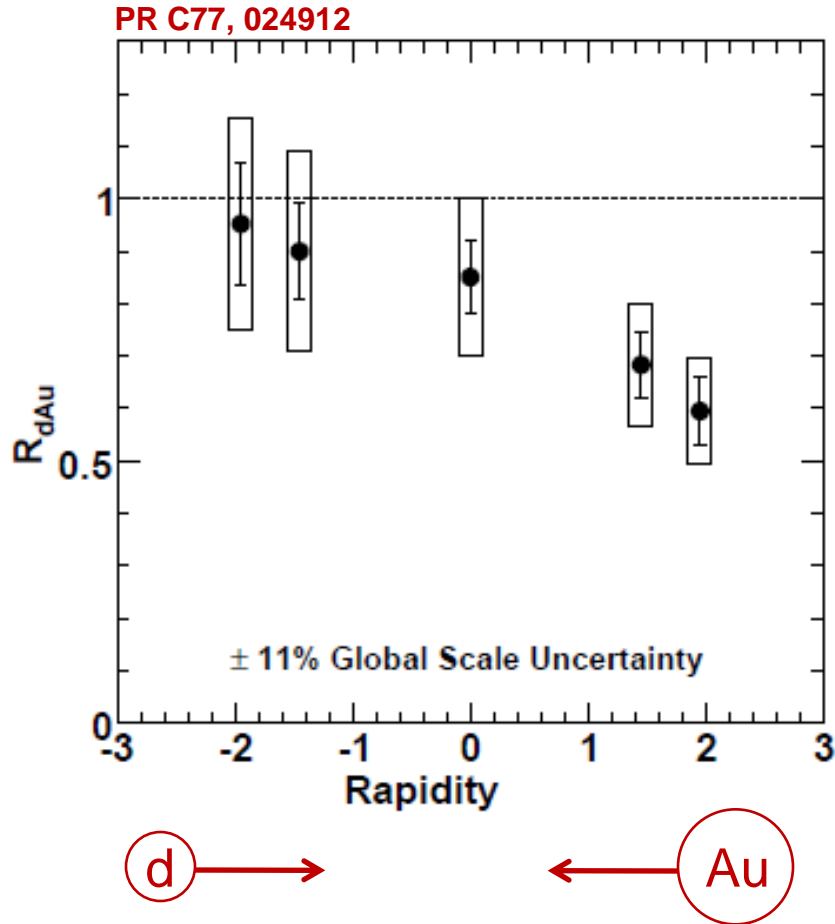
p+p summary

Progress are being made

- on the experimental side, to provide more precise data, and more observables:
other resonances;
heavy quarkonia *polarization* (not discussed here)
- on the theoretical side, to have calculations at higher orders; to include more contributions; and to simultaneously describe (and/or fit) multiple observables at different energies

II. d+Au collisions: Cold nuclear matter effects

J/ψ production in d+Au (1) 2003 data



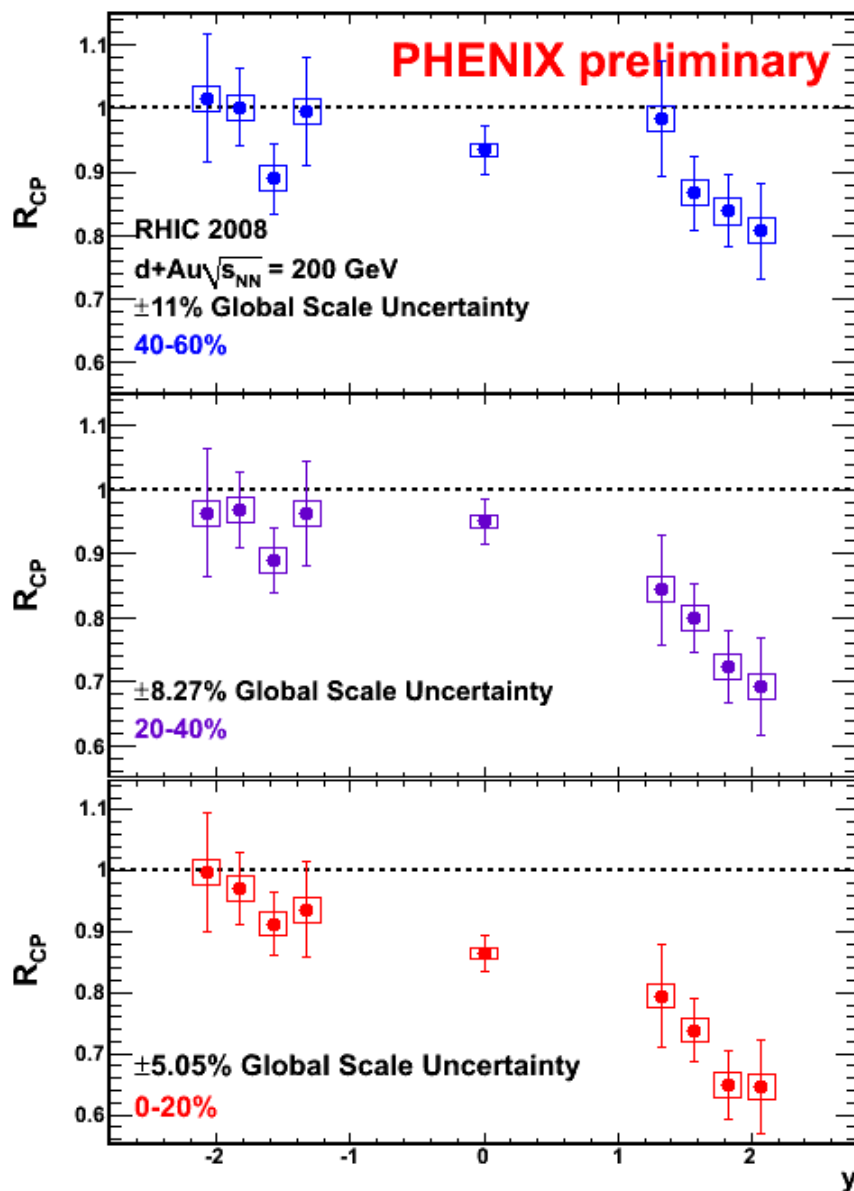
Nuclear modification factor:

$$R_{dA} = \frac{\text{yield in dA}}{N_{\text{coll}} \cdot \text{yield in pp}}$$

$y < 0$: Au going side. Large x in Au nuclei (x_2)

$y > 0$: deuteron going side. Small x in Au nuclei (where shadowing is expected)

J/ψ production in d+Au (2) 2008 data



2008 d+Au data sample = ~40 times more statistics than 2003 published results.

Enough statistics to provide 4 different centrality bins and 9 rapidity bins.

$$R_{CP}^{0-20\%} = \frac{N_{inv}^{0-20\%} / \langle N_{coll}^{0-20\%} \rangle}{N_{inv}^{60-88\%} / \langle N_{coll}^{60-88\%} \rangle}$$

Systematic errors largely cancel in R_{cp} .

$R_{cp} \sim 1$ at negative rapidity

$R_{cp} < 1$ and decreases with centrality at positive rapidity

Cold nuclear matter effects (CNM)

Anything that can modify the production of heavy quarkonia in heavy nuclei collisions (as opposed to p+p) in absence of a QGP

Initial state effects:

- Energy loss of the incoming parton
- Modification of the parton distribution functions (npdf)
- Gluon saturation (CGC)

Final state effects:

Dissociation/breakup of the J/ψ (or precursor $c\bar{c}$ quasi-bound state)

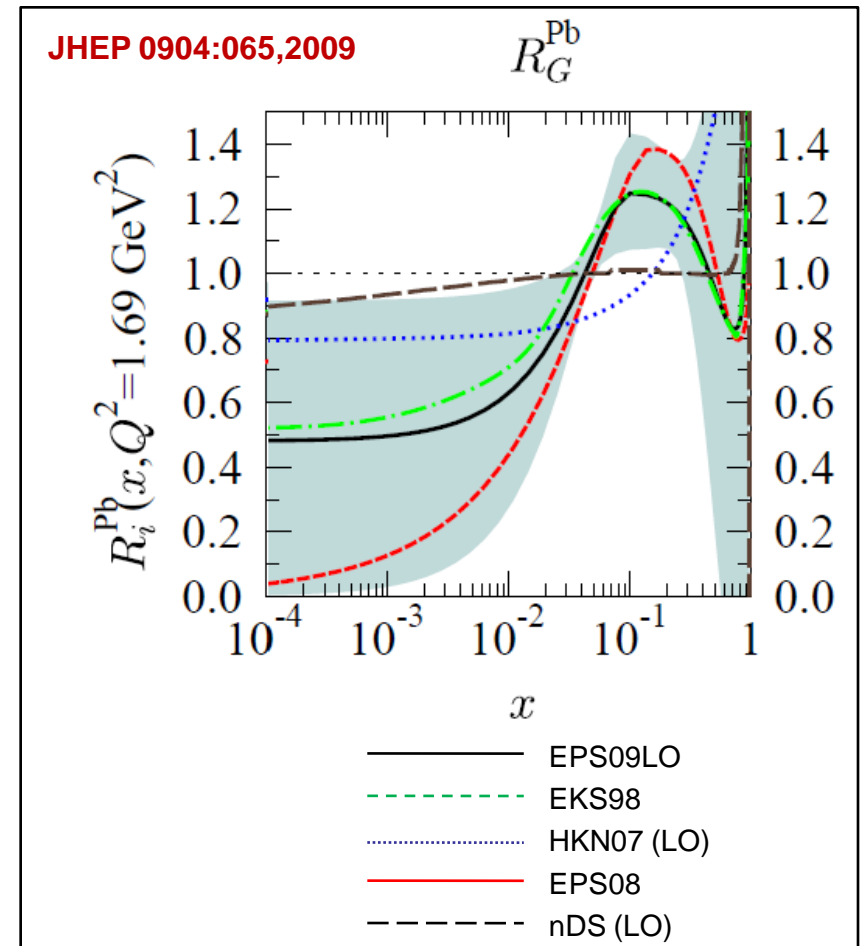
Modified PDF (npdf)

npdf refer to the fact that parton distribution (as a function of x_{bj}) inside a nucleon differs whether the nucleon is isolated or inside a nuclei.

Gluon nuclear npdfs are poorly known, especially at low x (shadowing region).

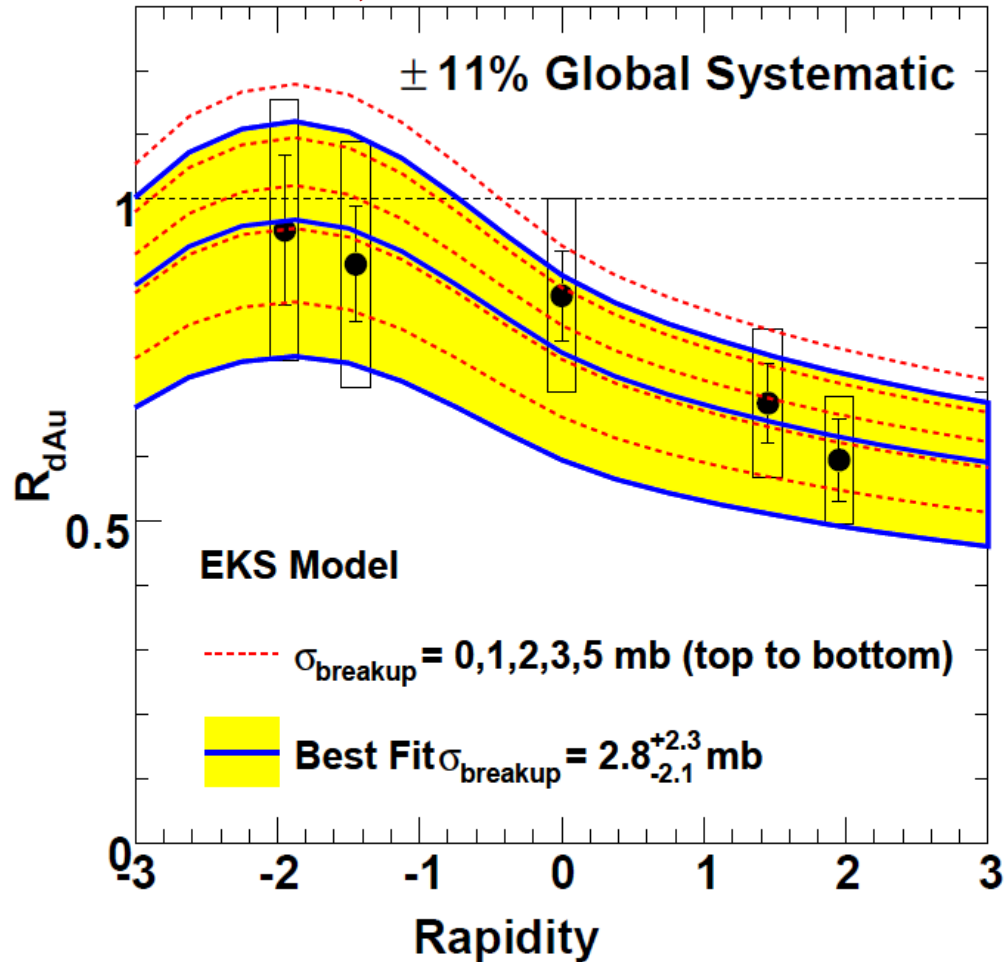
Various parametrizations range from

- little shadowing (HKN07, nDS, nDSg)
- moderate shadowing (EKS98, EPS09)
- large shadowing (EPS08)



npdf + σ_{breakup} vs data

PRC79:059901,2009



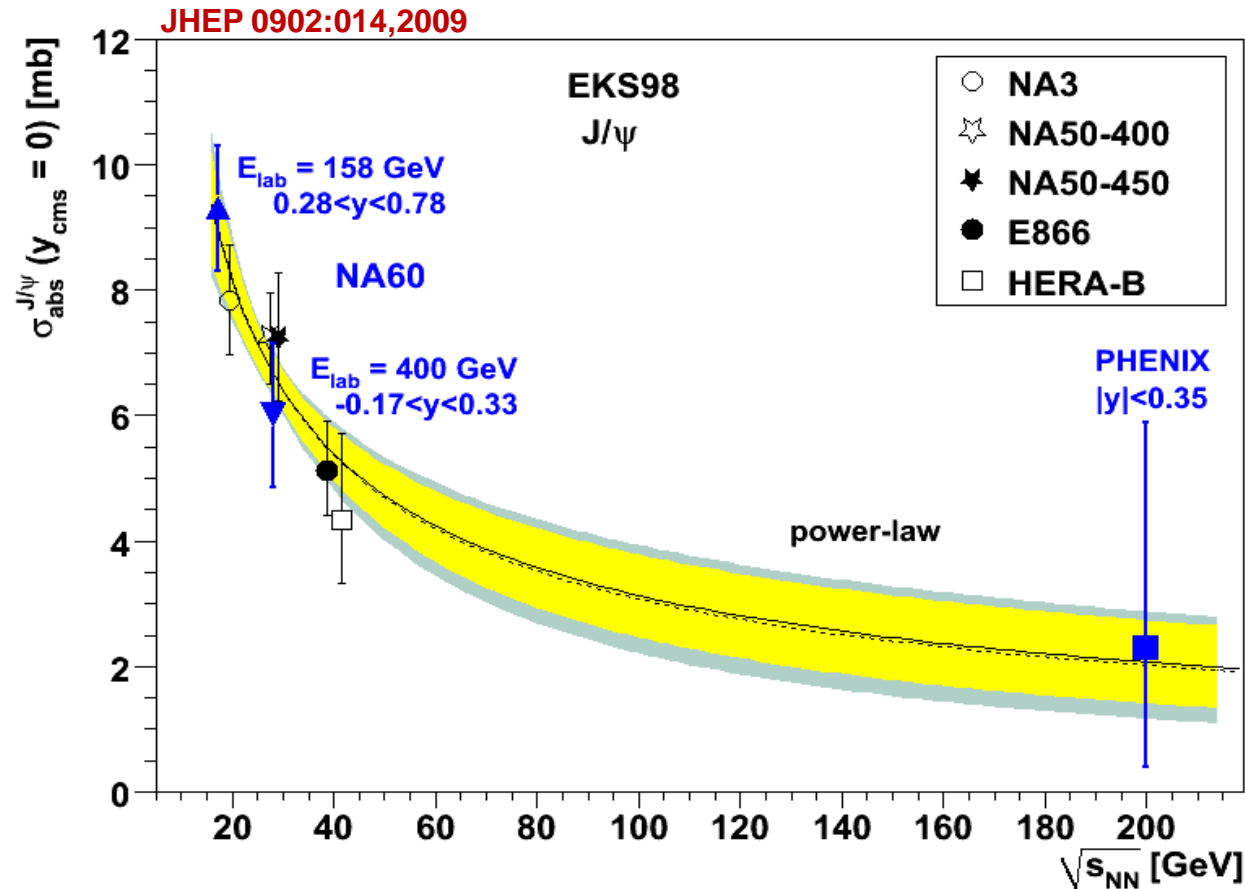
Take a npdf prescription (here EKS)

add a J/ψ (or precursors) breakup cross-section σ_{breakup}

Fit the best σ_{breakup} to the data, properly accounting for correlated and uncorrelated errors.

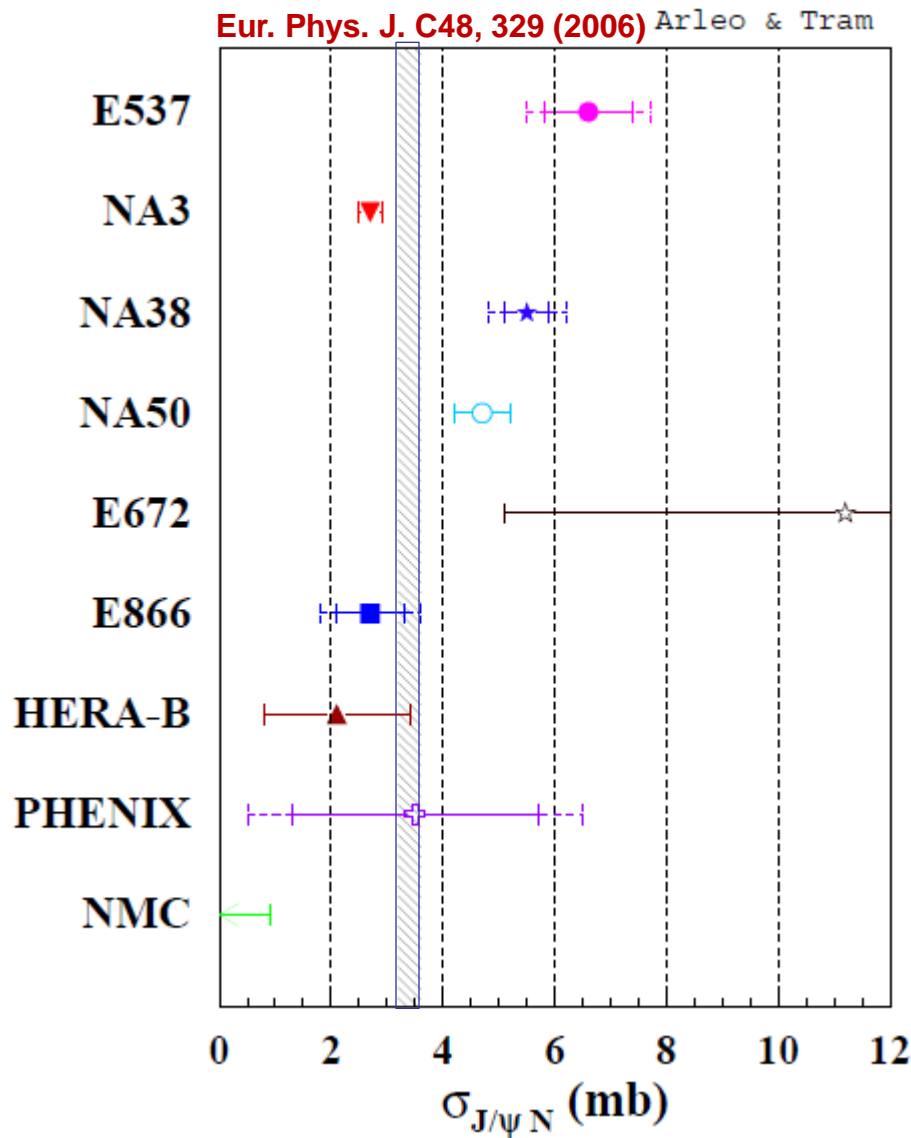
Here a unique cross-section is used across the entire rapidity range

Energy dependence of σ_{breakup} (1)

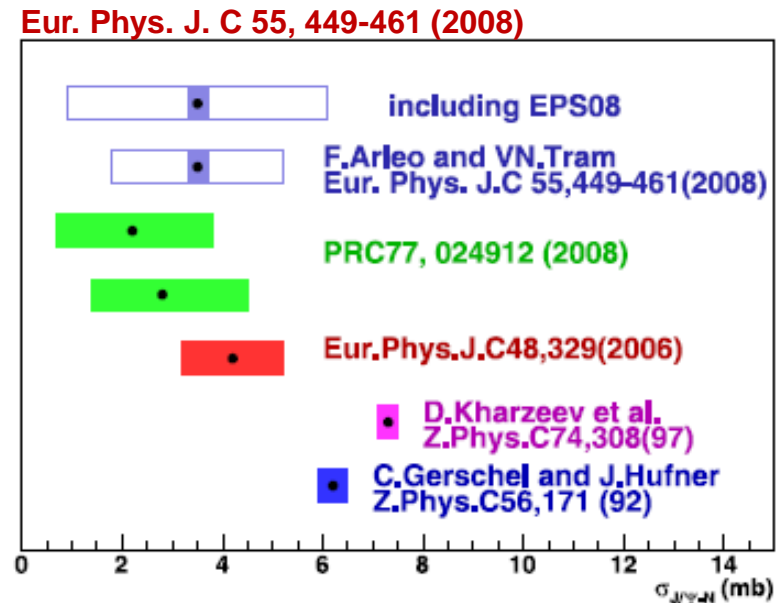


Putting σ_{breakup} as a function of \sqrt{s} and comparing to other experiments shows some sort of global trend, yet to be explained theoretically.

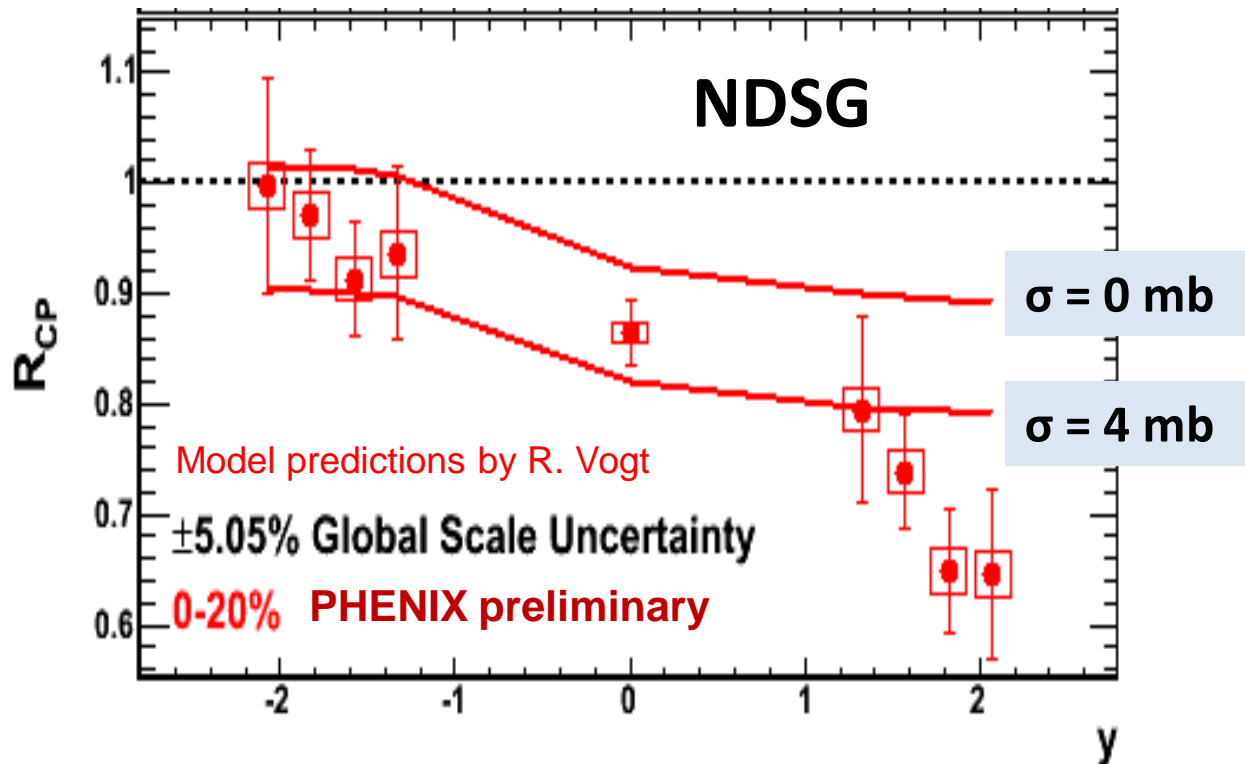
Energy dependence of σ_{breakup} (2)



Several systematic studies of σ_{breakup} (or $\sigma_{j/\psi N}$) are available, using all world data on J/ ψ lepto and hadro- production

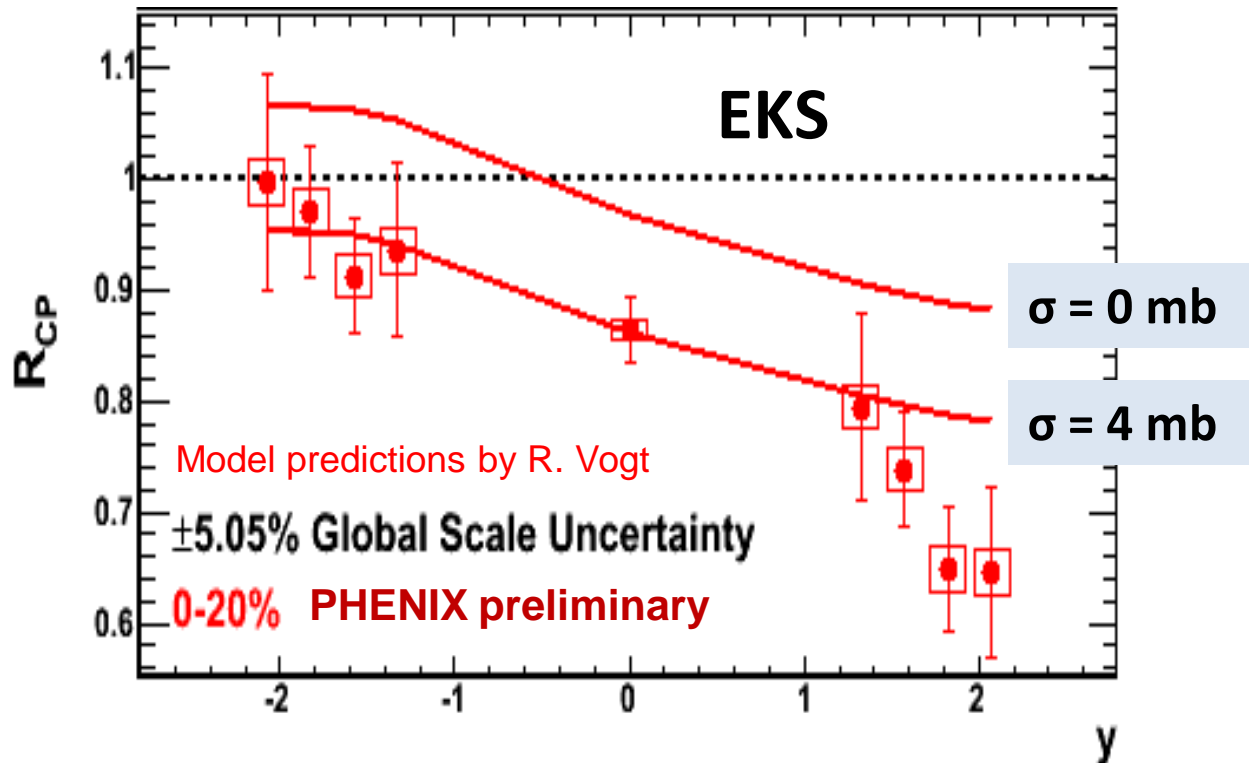


$n_{pdf} + \sigma_{breakup}$ vs data, using 2008 data set



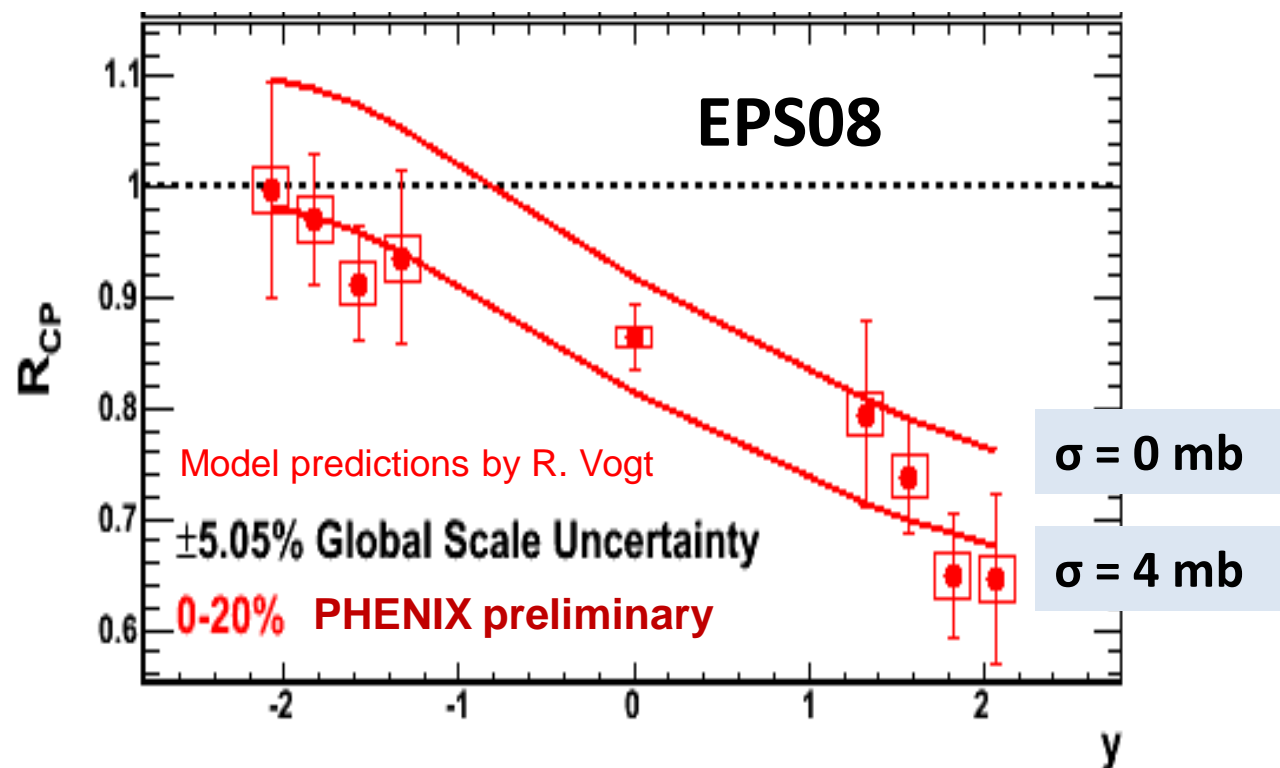
- Small and moderate shadowing fail to reproduce the high rapidity data

$n_{pdf} + \sigma_{\text{breakup}}$ vs data, using 2008 data set



- Small and moderate shadowing fail to reproduce the high rapidity data

$n_{pdf} + \sigma_{breakup}$ vs data, using 2008 data set

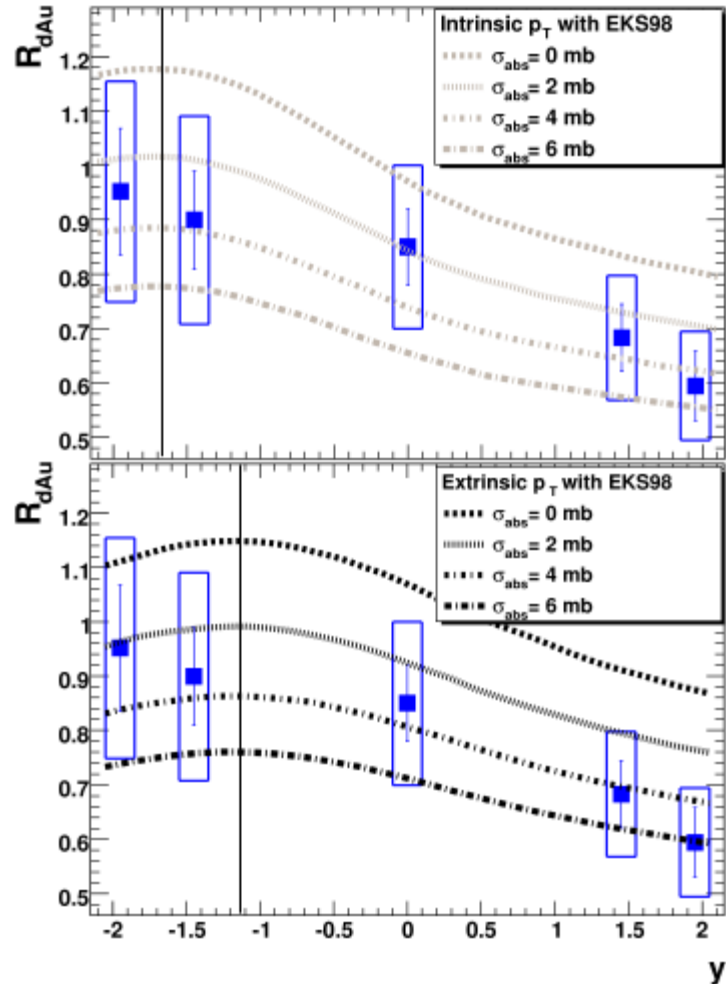


- Small and moderate shadowing fail to reproduce the high rapidity data
- Large shadowing (EPS08) does a better job, but does not really match lower energy data

Either we are missing some ingredient, or the full picture ($n_{pdf} + \sigma_{breakup}$) is not quite correct.

Impact of production mechanism (1)

arXiv:0912.4498



Statement from previous slide is even more true when properly accounting for the production kinematics :

How the p_T and y of the J/ψ relates to the initial partons' momentum (x_1 and x_2) depends on the production mechanism.

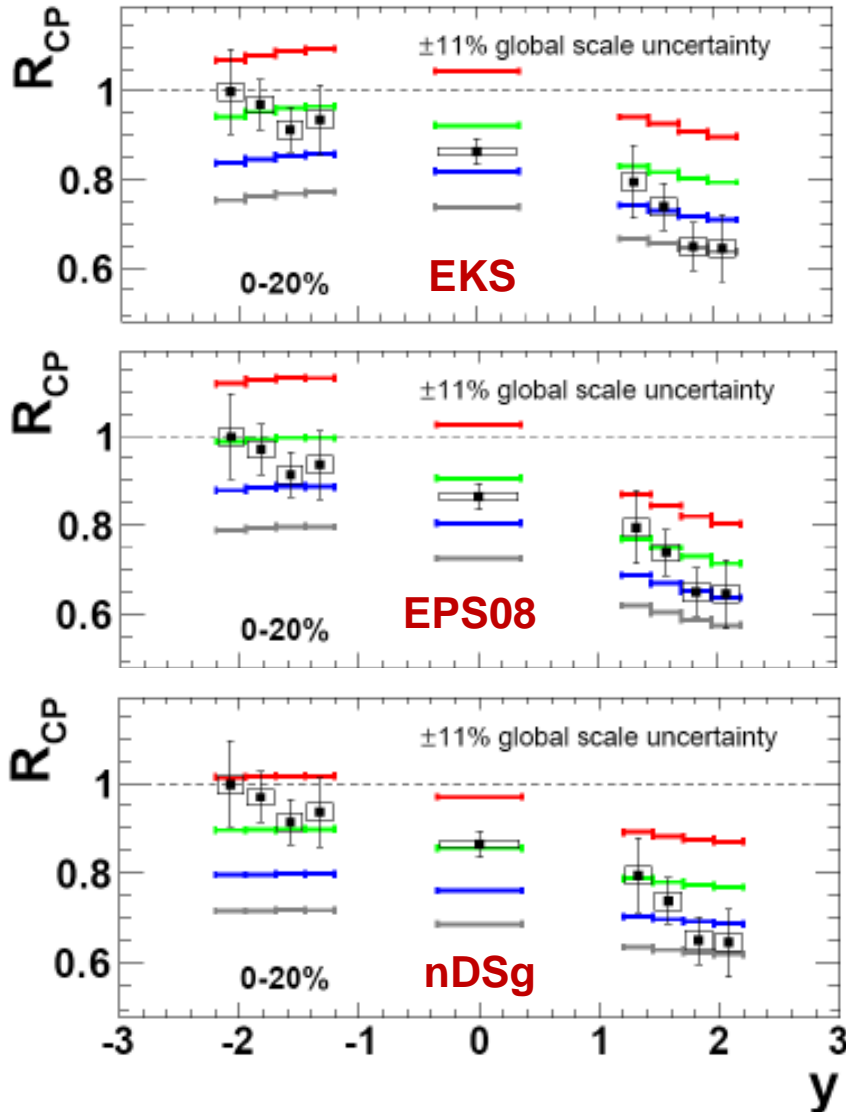
- for COM like processes, the reaction involved is of type $2 \rightarrow 1$ (*intrinsic* p_T)
- for CSM like processes, the reaction involved is of type $2 \rightarrow 2$, with a fraction of the momentum being carried by the third hard gluon (*extrinsic* p_T)

\Rightarrow A different x -region of the (n)pdf is sampled, which affects the suppression pattern.

The position of the anti-shadowing peak is shifted towards higher y ;
The effect of shadowing is smeared.

Impact of production mechanism (2)

arXiv:0912.4498

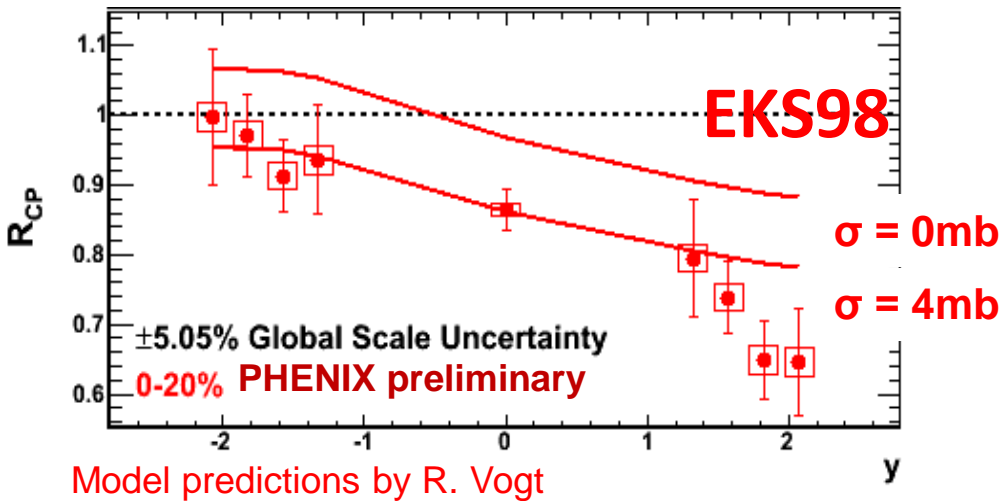


Here, EKS, EPS08 and nDSg shadowing are used, compared to most central 2008 d+Au data.

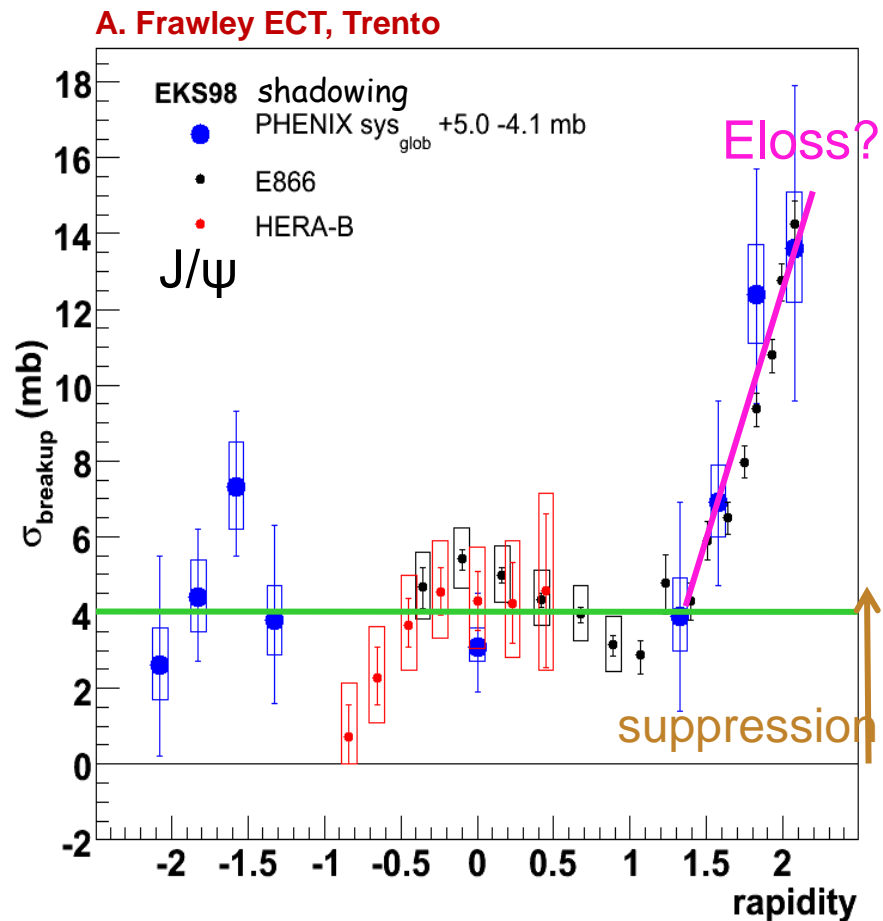
Various colors correspond to increasing $\sigma_{breakup}$.

As before, the calculations fail to describe the most forward suppression.

Effective σ_{breakup} vs rapidity



- shadowing + fixed σ_{breakup} don't match the observed rapidity dependency
- Use d+Au data to extract effective σ_{breakup} as a function of rapidity which parameterizes all the effects that shadowing is missing
- Same trend is observed at mid and forward rapidity by E866 and HERA-B

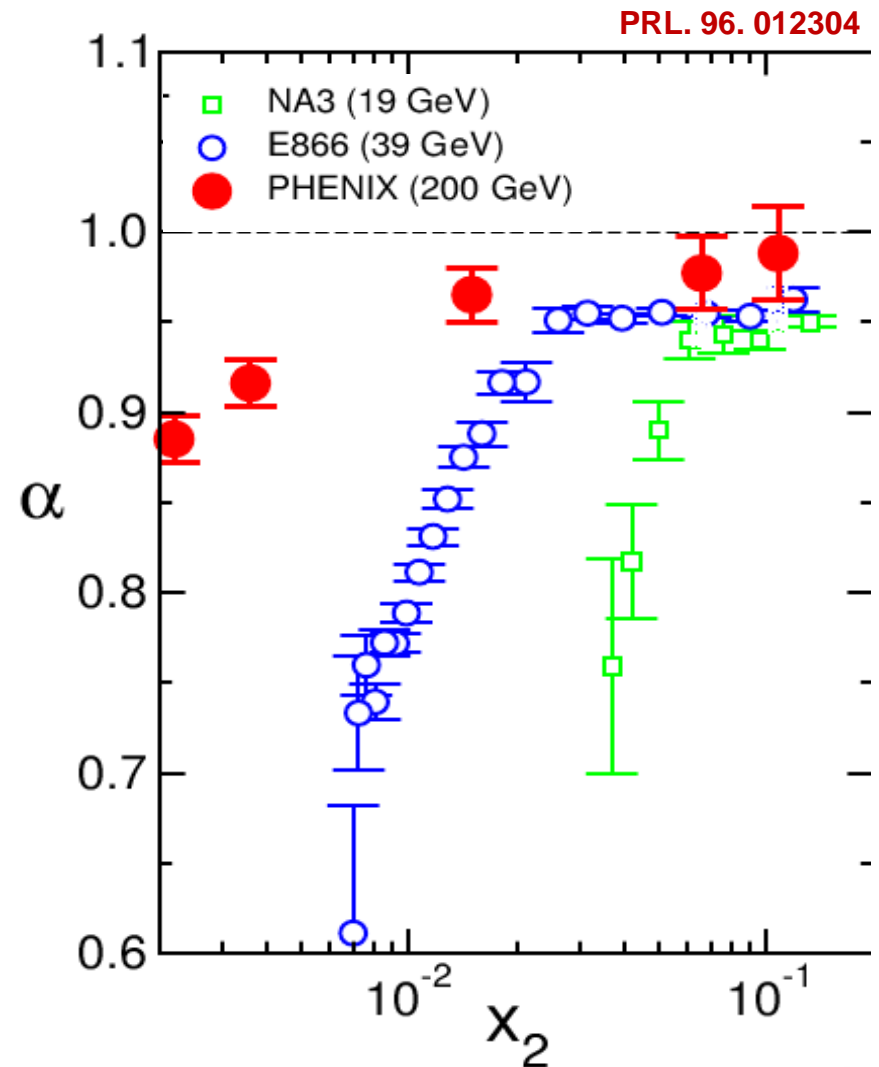


x_1, x_2, x_F dependency

Here use alpha instead of RdAu

$$\sigma_{pA} = \sigma_{pp} A^\alpha$$

npdf + σ_{breakup} picture expects scaling as a function of x_2 , which is obviously not observed.



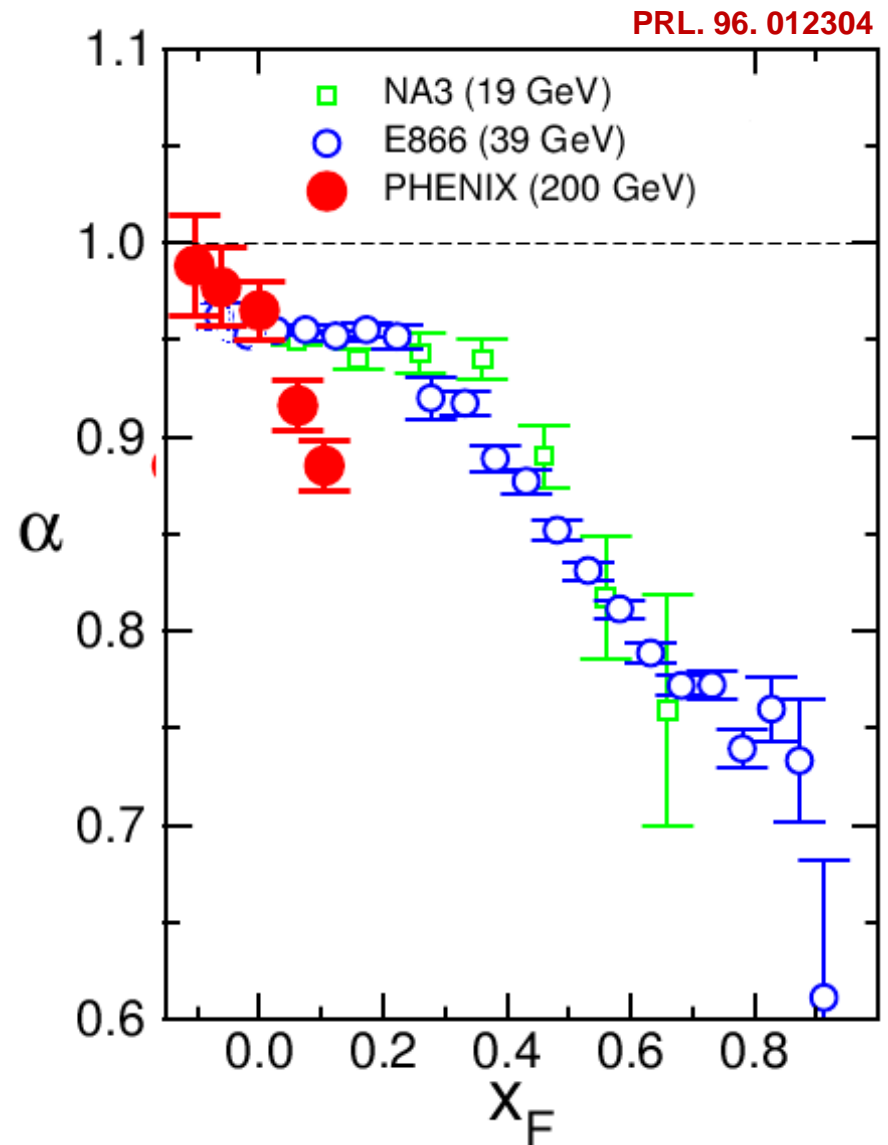
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Somewhat better (though not perfect) scaling observed as a function of x_F .



x_1, x_2, x_F dependency

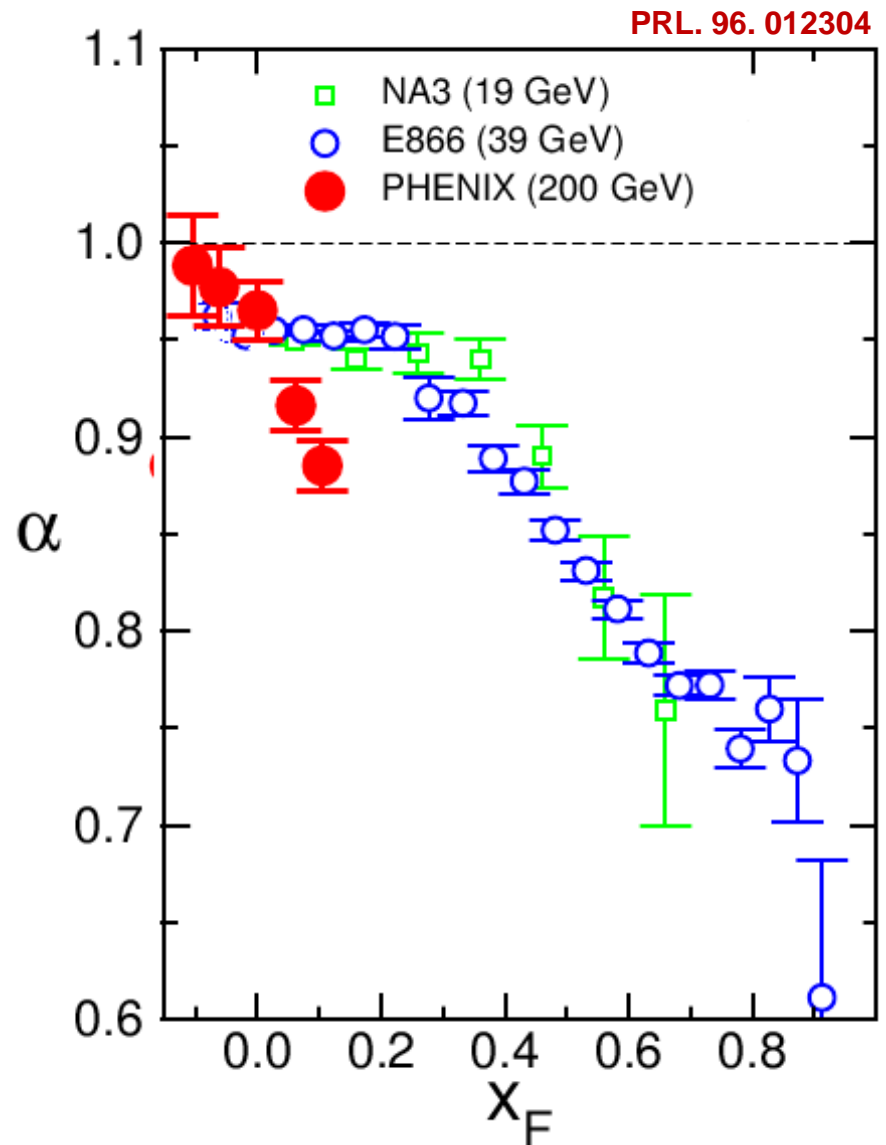
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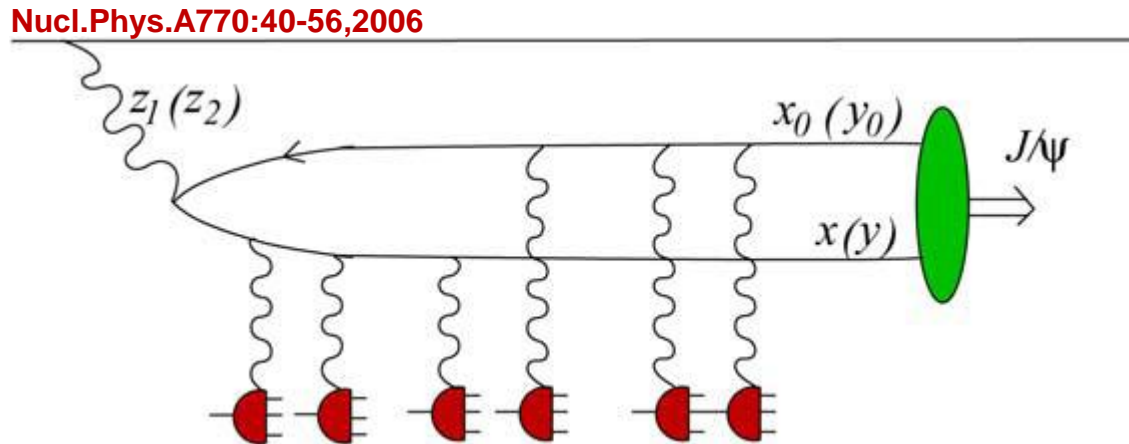
Somewhat better (though not perfect) scaling observed as a function of x_F .

At least for NA3 and E866, the high x_F decrease can be explained by initial state energy loss.



Gluon saturation (1)

Provides a different picture of the dAu collision and how J/ψ is produced:



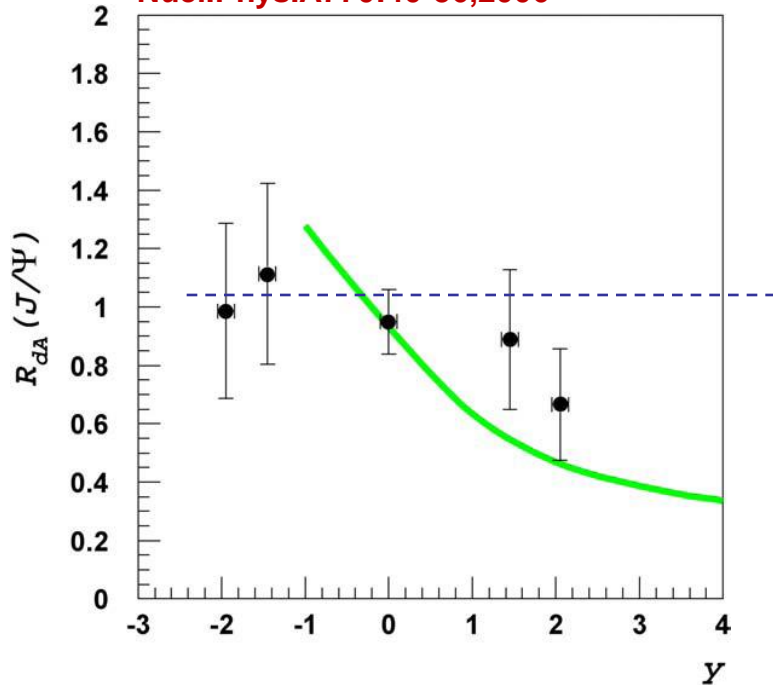
At low enough x_2 (in the target nuclei), the gluon wave functions overlap. The $c\bar{c}$ pair from the projectile parton interacts with all nucleons from the target in a coherent way, resulting in the J/ψ formation.

This is applicable at low x_2 (forward rapidity) only;

makes the use of σ_{breakup} irrelevant in this regime.

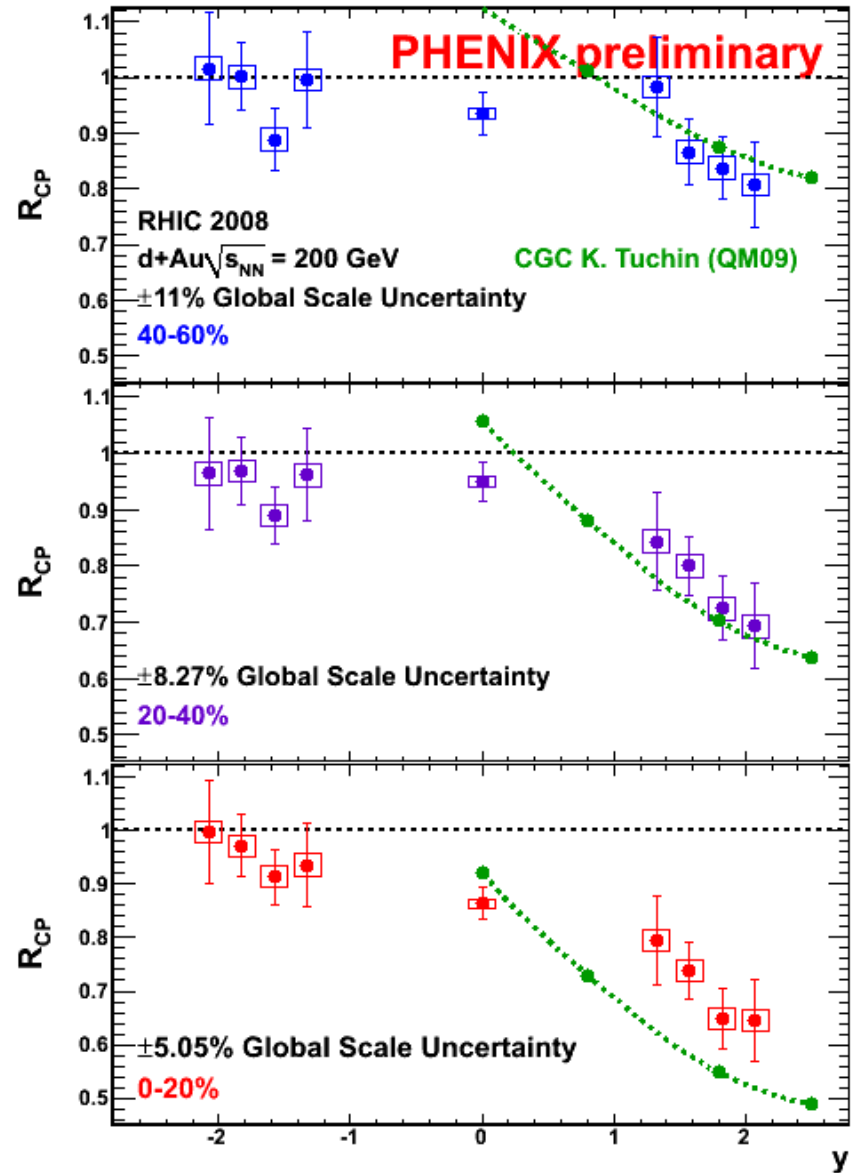
Gluon saturation (2)

Nucl.Phys.A770:40-56,2006



Geometrical description of the collision is oversimplified in both plots.

Right plots are an early comparison of the same calculation to 2008 R_{CP} data

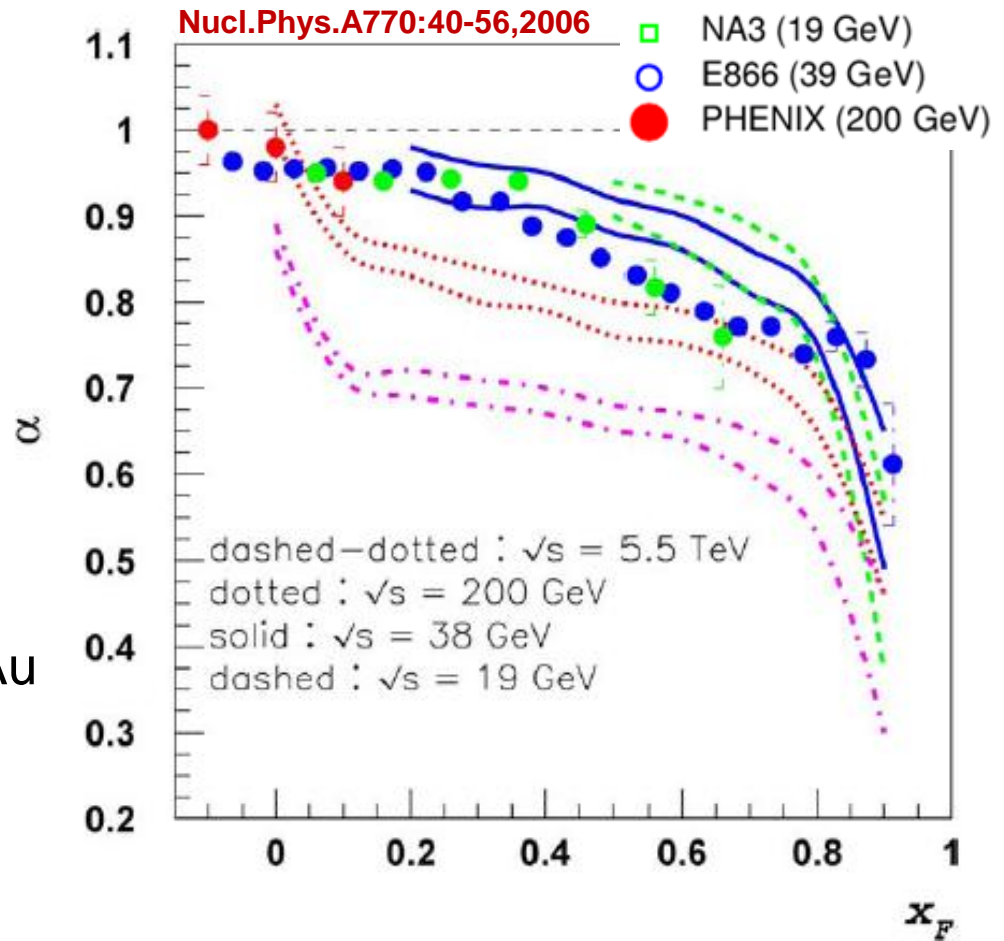


Gluon saturation (3)

CGC formalism aims to explain

- why x_2 scaling is not observed;
- why approximate x_F scaling is observed, provided that the energy difference between the experiments being compared is not too large

Calculations also available for Au+Au collisions ([PRL.102:152301,2009](#))



d+Au summary

Two approaches emerge for describing Cold Nuclear Matter effects on J/ψ production in d+Au collisions:

- **(poorly constrained) npdf + initial energy loss + σ_{breakup}**
Here it is important to take all effects into account if one wishes to describe all the available data (notably at low x_2)
- **gluon saturation CGC**
It provides an alternative description of the collision at low x_2 , and (at least qualitative) explanations to some of the observed effects.

however:

- It has no prediction for high x (right ?).
- How do we proceed in this regime?
- Fall back to the first approach ?
- How does CGC connect to the more standard approach above ?

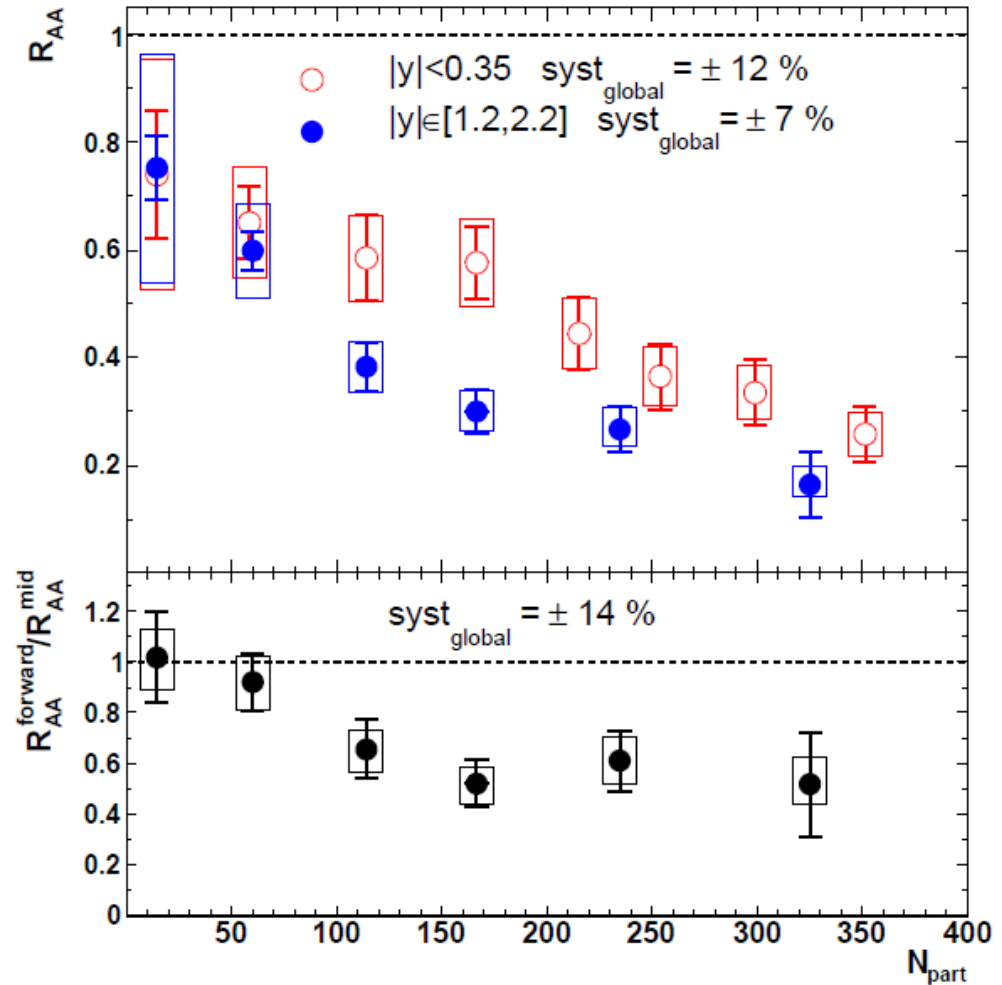
III. A+A collisions: anomalous suppression ?

J/ψ R_{AA} vs N_{part}

2004 data published in

PRL 98 (2007) 232301

J/ψ R_{AA} vs N_{part} , p_T and rapidity



J/ψ R_{AA} vs N_{part}

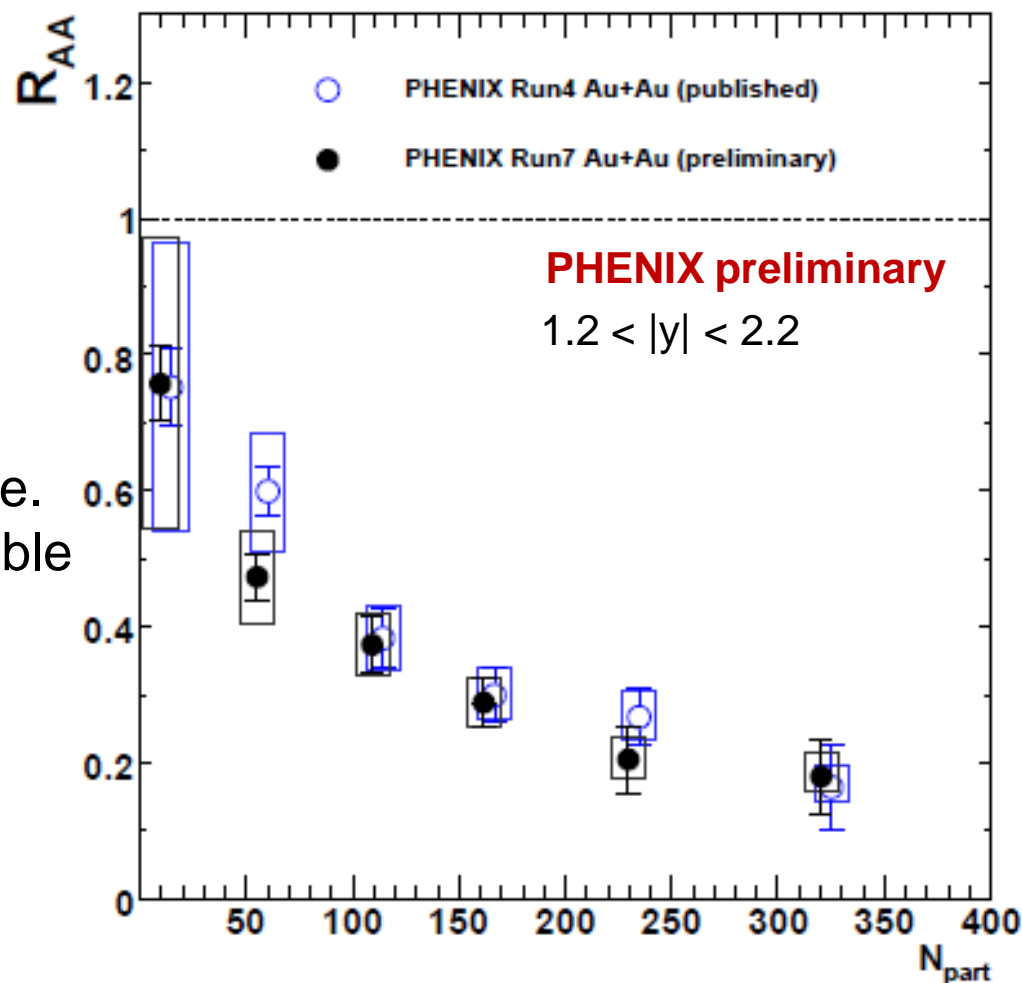
2004 data published in

PRL 98 (2007) 232301

J/ψ R_{AA} vs N_{part} , p_T and rapidity

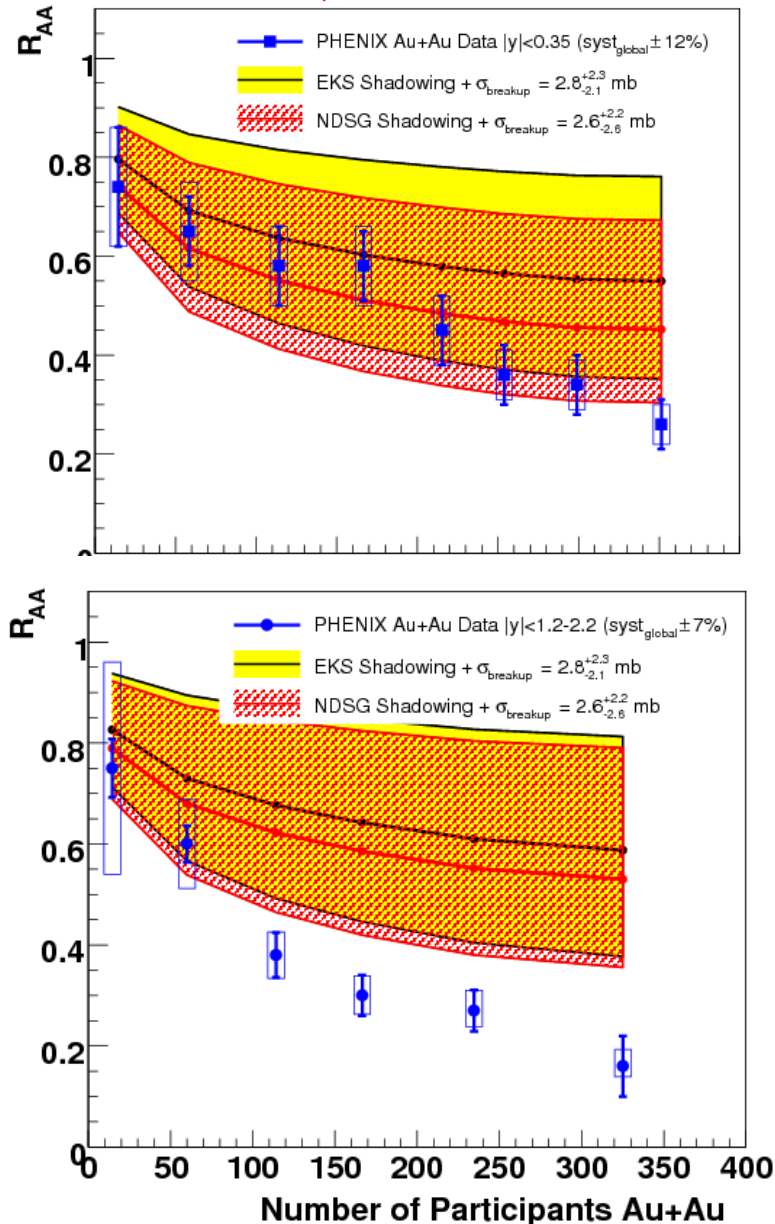
2007 data ($\sim x4$ statistics) are still being analyzed.

Preliminary R_{AA} (and v_2) is available. Final results should become available soon.



J/ψ R_{AA} and extrapolated CNM (1)

PRC79:059901,2009



Here a **unique break-up cross** section is derived from the mid and forward rapidity d+Au data (2003), for two npdf prescriptions, and extrapolated to Au+Au

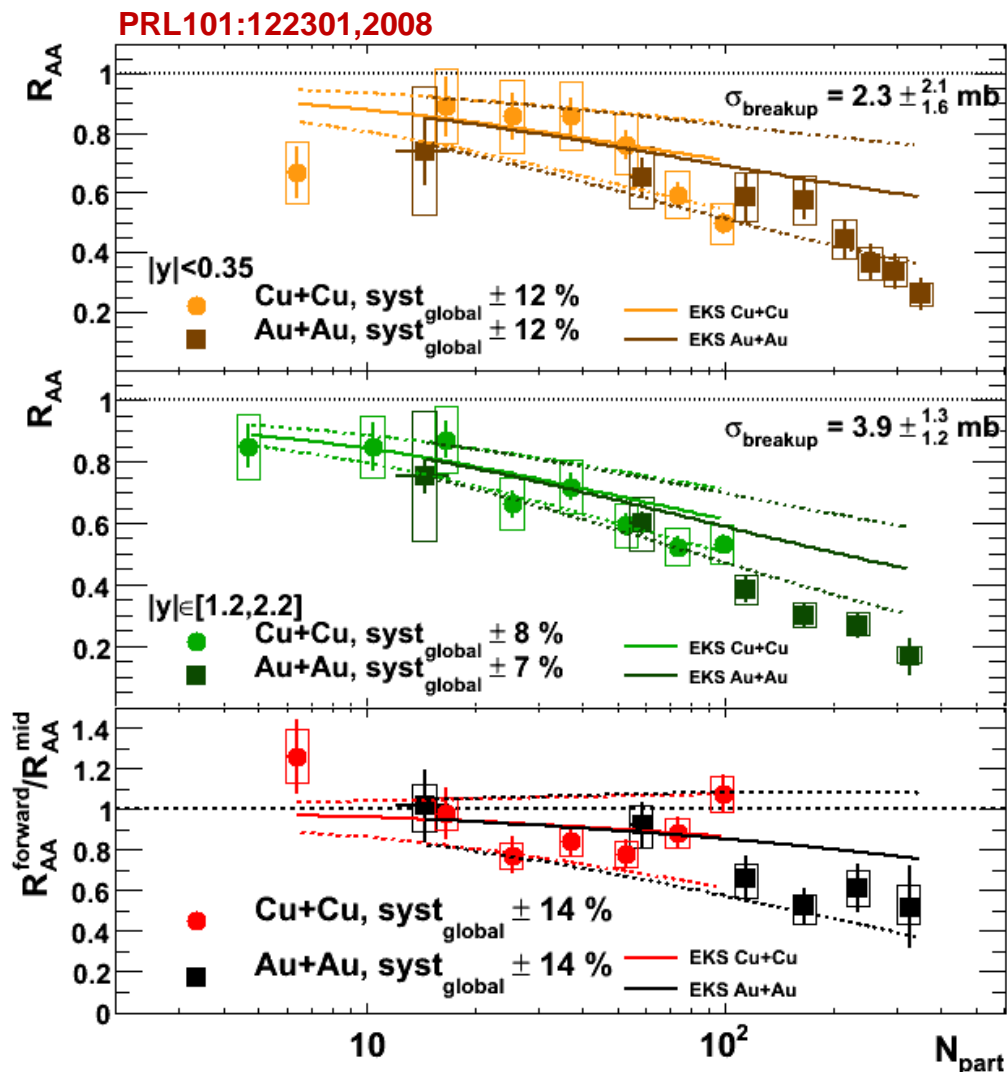
Error bars from CNM are large;

Difference between npdf prescriptions is modest;

Even in the worst case, there is some additional suppression observed in most central Au+Au collisions, beyond CNM;

There **appear to** be more anomalous suppression at forward rapidity.

J/ψ R_{AA} and extrapolated CNM (2)



Data are from 2005 Cu-Cu and 2004 Au-Au.

Lines are cold nuclear matter effects extrapolated from 2003 d-Au data, **using different $\sigma_{breakup}$ for mid and forward rapidity**

Cu-Cu and Au-Au ratios match well where they overlap.

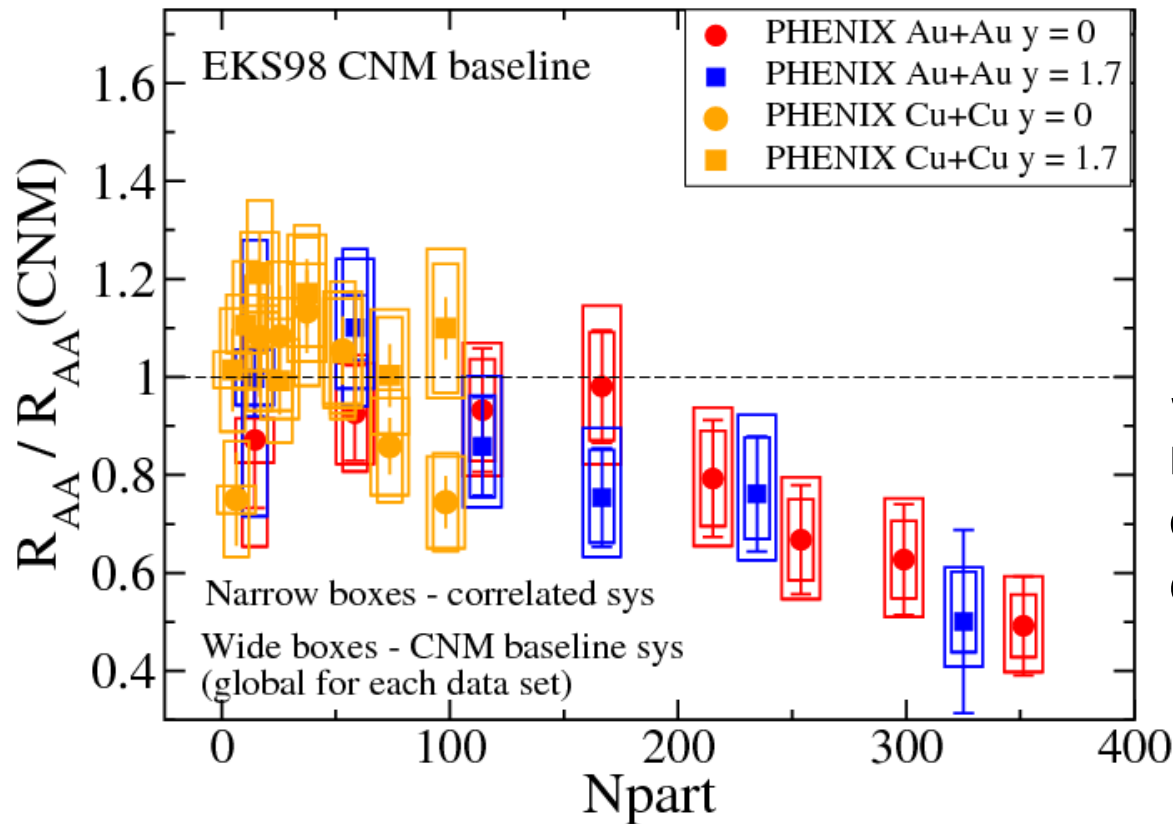
In Au+Au the suppression is larger than expected from CNM

There is (still) more suppression at forward rapidity than at mid-rapidity, **but the difference can be absorbed by CNM**

J/ψ R_{AA} over CNM in Cu+Cu and Au+Au

Calculations from A. Frawley (CATHIE, INT workshop)

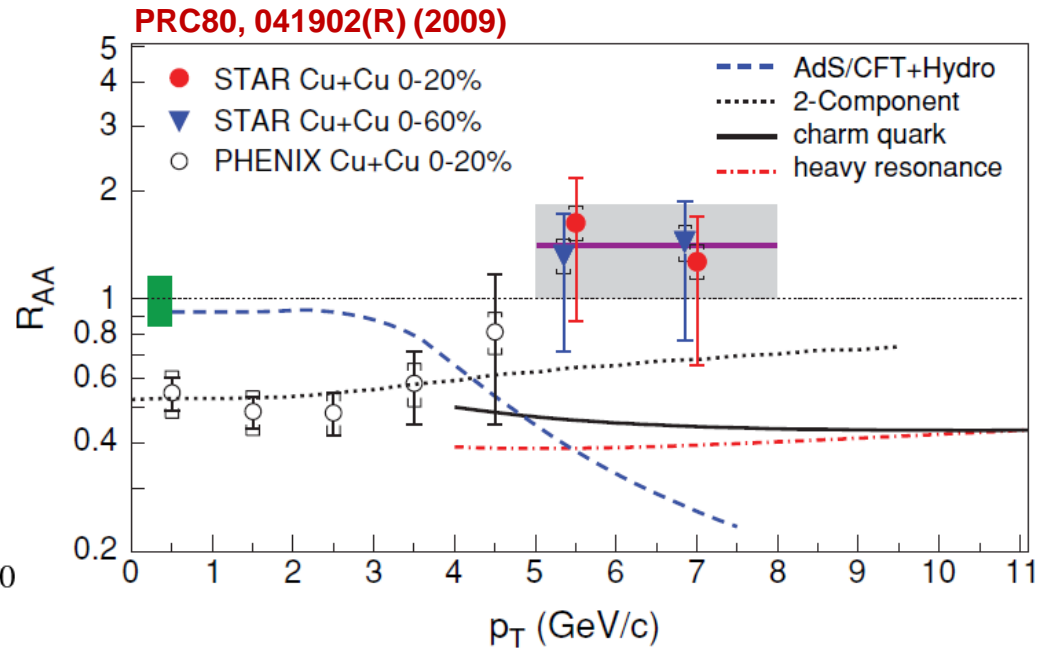
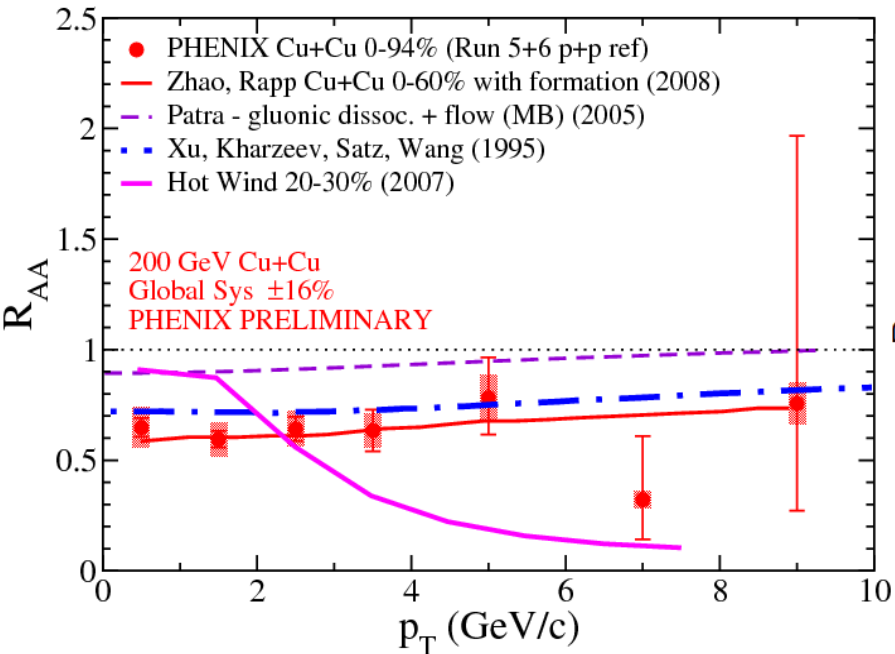
σ_{breakup} and errors estimated from 2008 data



Differences between mid and forward rapidity measurement are washed out.

Suppression beyond cold nuclear matter effects is observed, consistent with deconfinement

p_T dependency (1) Cu+Cu collision



Left is minimum bias Cu+Cu collisions

Right is 0-20% central Cu+Cu collisions, adding STAR high p_T data (red points)

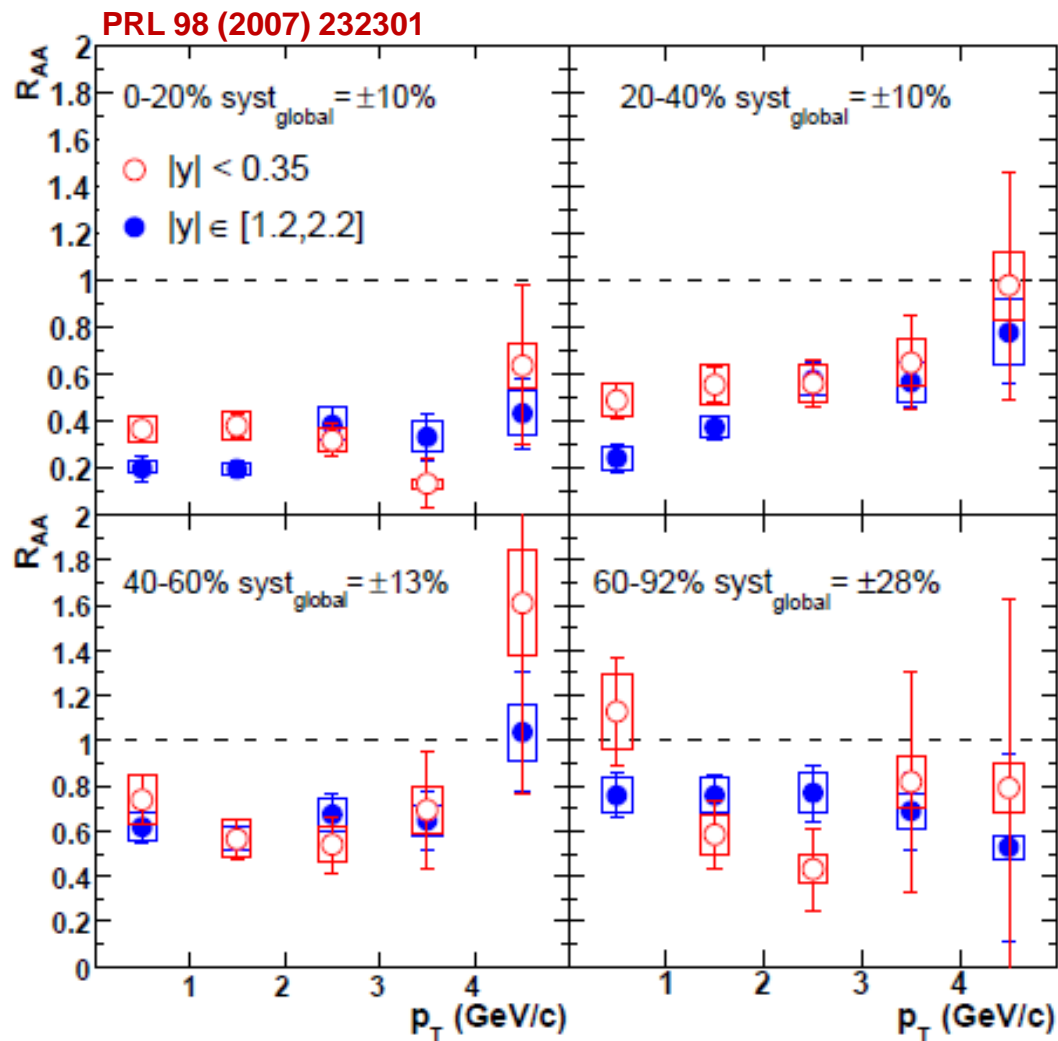
Possible increase of R_{CuCu} observed at high p_T

p_T dependency (2) Au+Au collisions

Some hint of increase with p_T for central collisions, but:

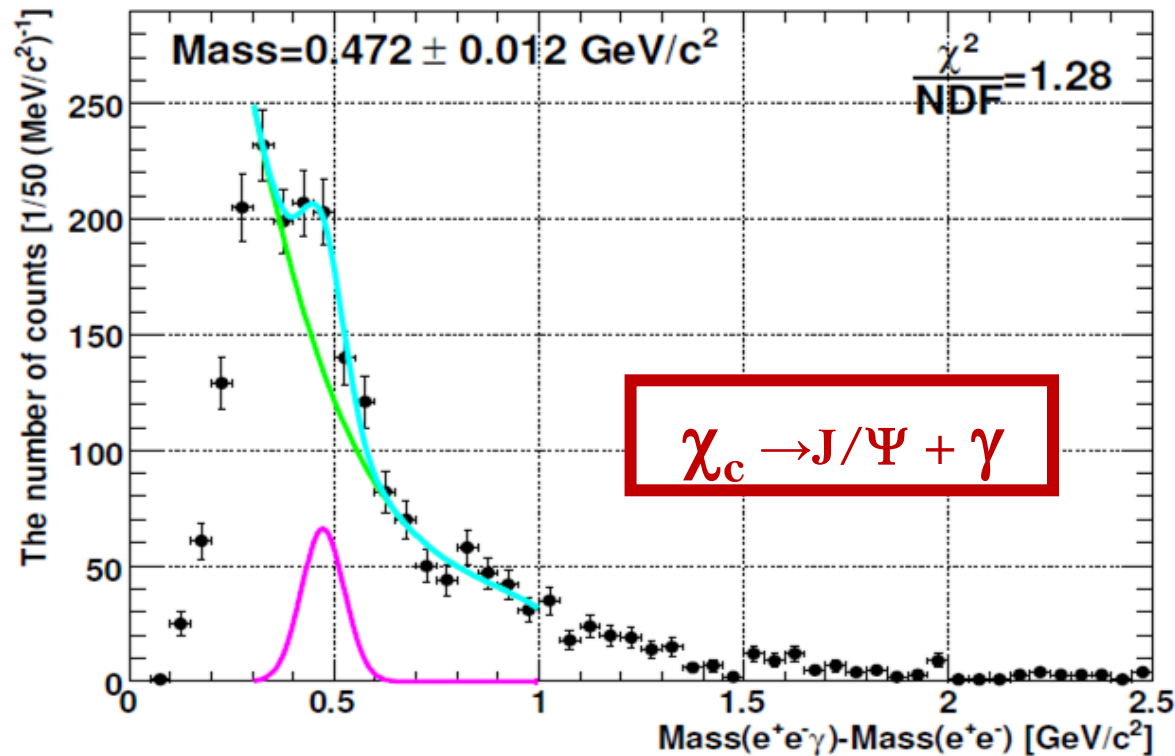
- errors are large
- p_T coverage is quite modest.

Note that an increase of R_{AA} at high p_T is consistent with an increase of $\langle p_T^2 \rangle$ from p+p to A+A (Cronin effect ?)



IV. More tools: other resonances

χ_c production



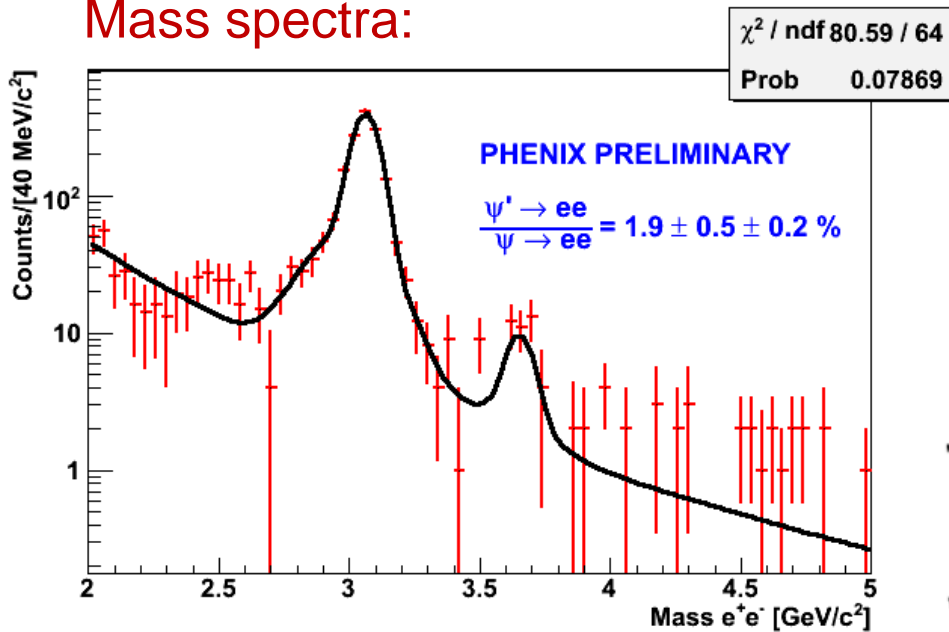
Measured at mid rapidity via di-electron + photon in EMCal
Provides: feed-down contribution to J/ψ

J/ψ from $\chi_c < 42\%$ (90% CL)

PHENIX preliminary

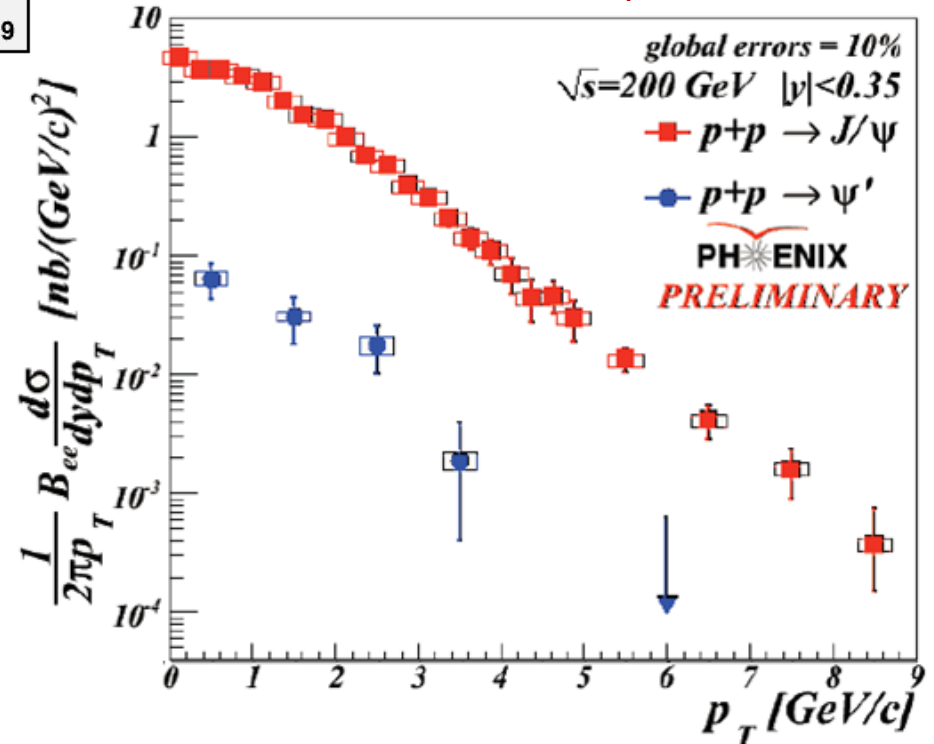
ψ' production

Mass spectra:

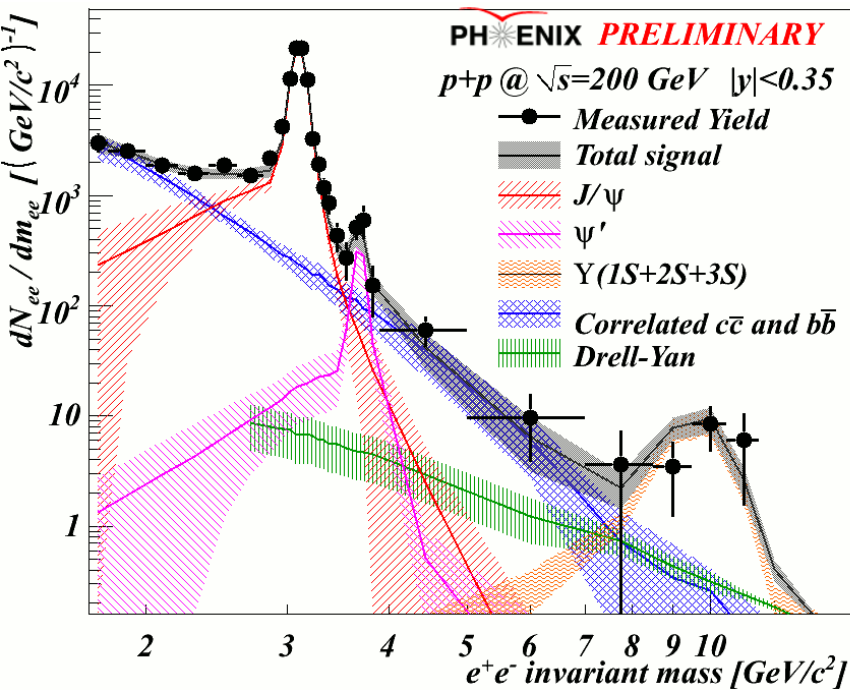


J/ψ from $\psi' = 8.6 \pm 2.5 \%$

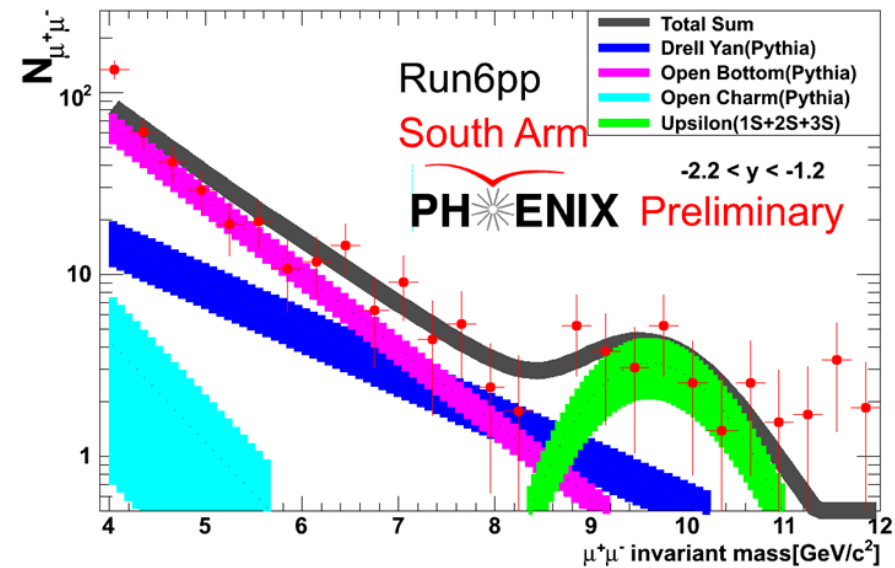
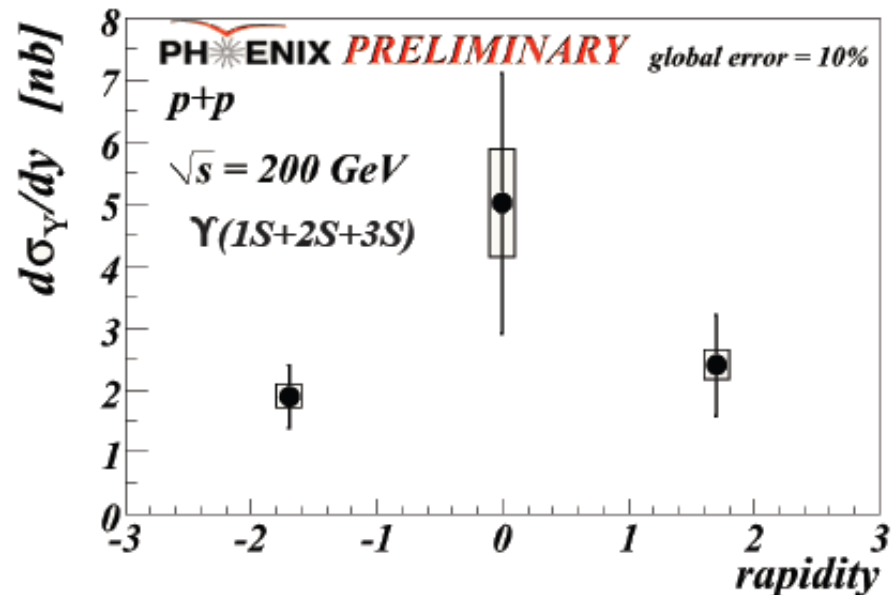
Cross section vs p_T :



Υ production in p+p collisions



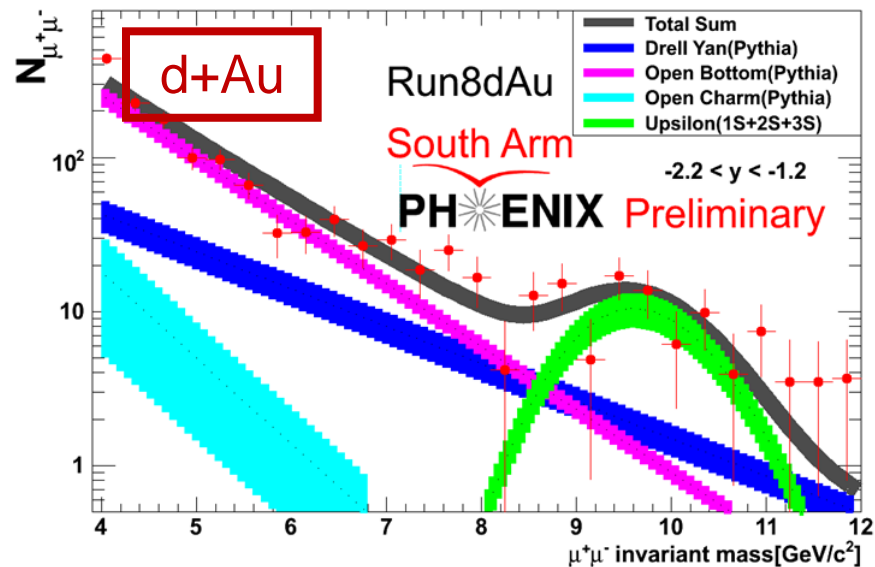
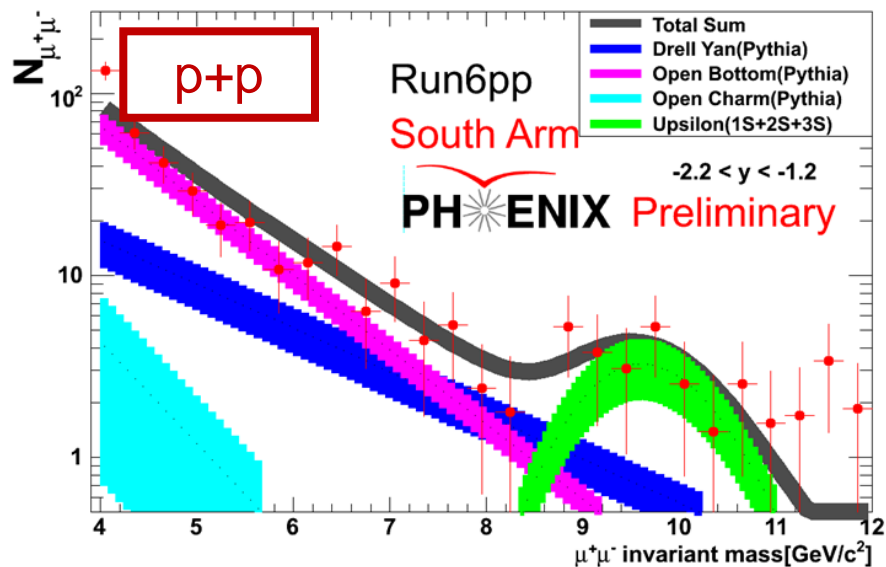
Rapidity dependence:



Cross section:

$$BR * \frac{d\sigma}{dy} \Big|_{|y|<0.35} = 114^{+46}_{-45} \text{ pb}$$

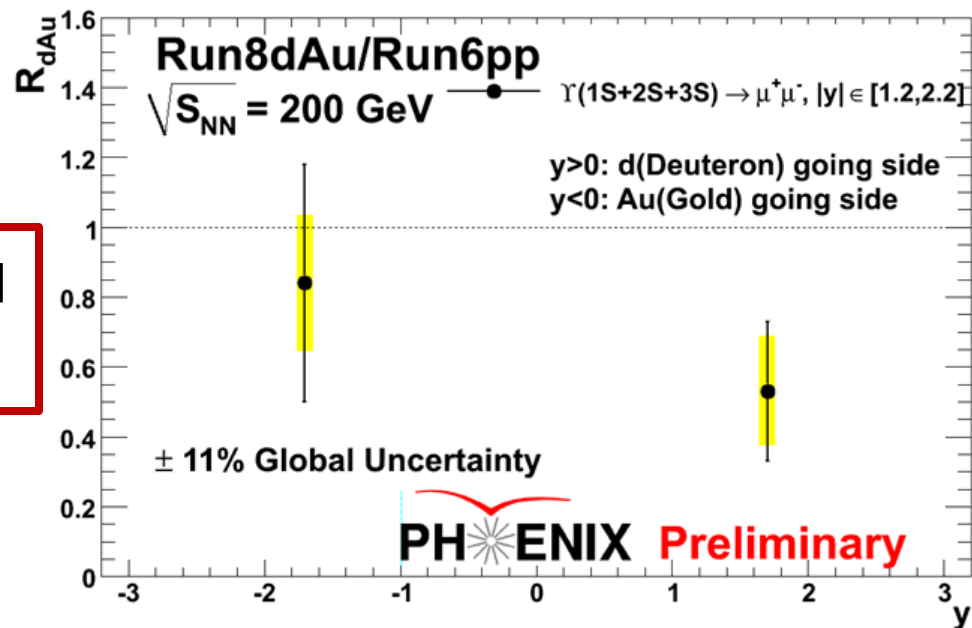
Υ R_{dAu}



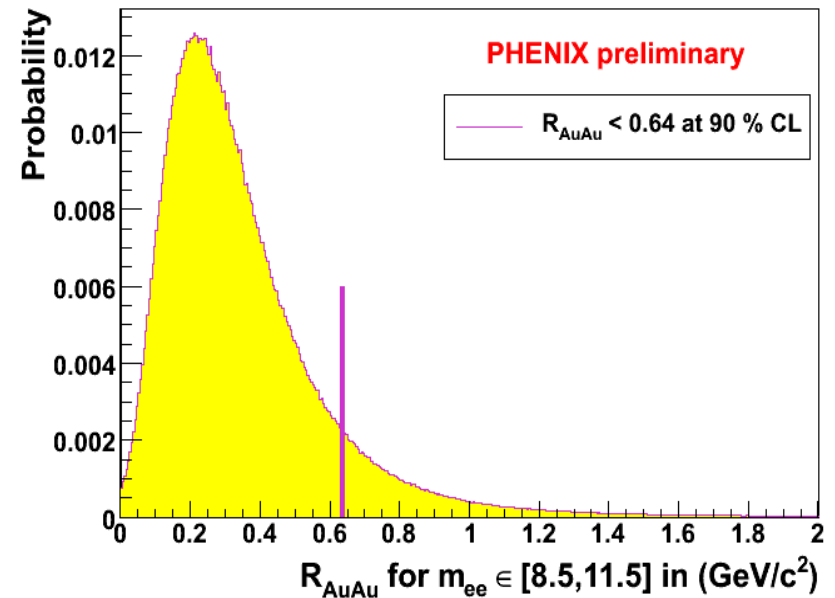
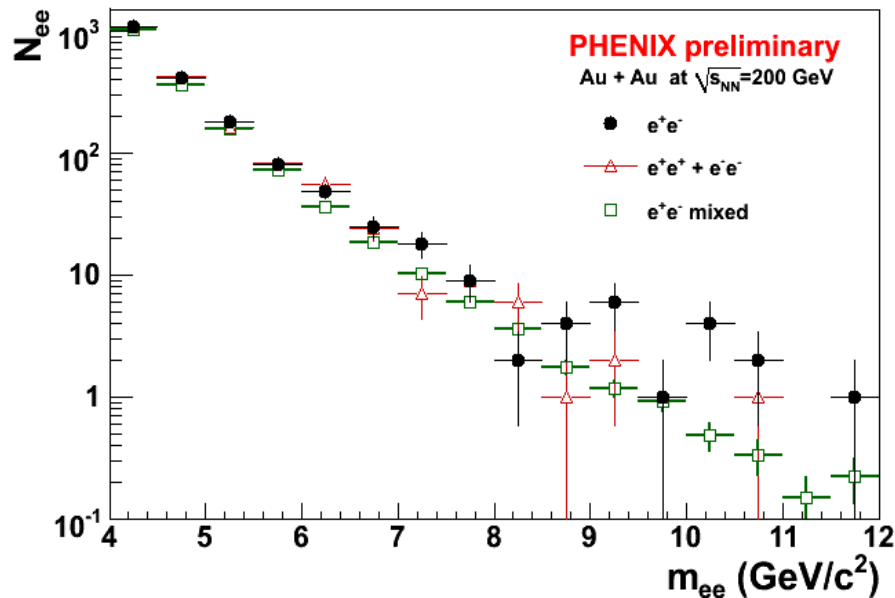
First Υ measurement at forward rapidity ($1.2 < |y| < 2.2$) in d+Au collisions

$$R_{dAu} = 0.84 \pm 0.34(\text{stat.}) \pm 0.20(\text{sys.}), y [-2.2, -1.2]$$

$$R_{dAu} = 0.53 \pm 0.20(\text{stat.}) \pm 0.16(\text{sys.}), y [1.2, 2.2]$$



Υ (or rather: high mass di-leptons) R_{AA}



- Compute a double ratio of (high mass dileptons)/(J/ ψ) between p+p and Au+Au, to cancel systematics
- Using J/ ψ R_{AA} , derive a 90% CL for high-mass dileptons R_{AA}

$R_{AuAu} [8.5, 11.5] < 0.64$ at 90% C.L.

Conclusions

Understanding heavy quarkonia production in p+p collisions has shown a lot of activity recently, notably due to the availability of

- more precise J/ψ data
- other resonances

(not to mention J/ψ “polarization”, not discussed here)

Two approaches emerge for describing Cold Nuclear Matter effects on J/ψ production in d+Au collisions:

- (poorly constrained) npdf + initial energy loss + σ_{breakup}
- gluon saturation CGC (at low x)

Note that the interplay between the two is not clear (to me)

It is critical to understand *all* these CNM effects, and how they extrapolate to Au+Au, if one wants to be quantitative about any “anomalous” suppression in Au+Au